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VOLUME 2

EDITED BY CHRYSSOSTOMIDIS AND JOHANSSON

10th International Conference on Computer Applications in Shipbuilding

Volume 2

About ICCAS

ICCAS is short for International Conference on Computer Applications in Shipbuilding. The ICCAS conferences are initiated by IFIP WG5.6. They are held every 2 to 3 years. Previous conferences were held in:

Tokyo 1973	Trieste 1985
Gothenburg 1976	Shanghai 1988
Glasgow 1979	Rio de Janiero 1991
Annapolis 1982	Bremen 1994

Yokahama 1997

The ICCAS '99 Conference

ICCAS '99 was organized by the Massachusetts Institute of Technology Sea Grant College Program and the Department of Ocean Engineering at MIT. The conference was held at MIT in Cambridge, Massachusetts, USA on June 7-11, 1999.

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10th International Conference on Computer Applications in Shipbuilding

ICCAS '99

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Volume 2

Edited by C. Chryssostomidis
Massachusetts Institute of Technology

and

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PREFACE

Advances in information technology have revolutionized aspects of shipbuilding, from preliminary design to assembly and shipyard management. This technology will continue to be an important factor in future productivity and performance. ICCAS '99 at the Massachusetts Institute of Technology brought together a broad cross section of the international academic and industrial community to address these issues. The papers presented ranged the full spectrum, from reviews of operational experience with existing computer applications to discussions of emerging advances in information technologies destined to become the basis for the next generation of shipyard computer systems.

Papers were grouped into the following areas:

CAD/CAM/CIM Systems
Operation and Management
Product Modelling
Emerging Information Technologies
Information Technology Infrastructure
Detailed and Production Design
Preliminary Design
Assembly and Construction

In all, 86 papers were presented at ICCAS '99, and they are all published in these three volumes.

We deeply appreciate the efforts of the committee members, contributors and participants, all of whom have helped this conference to be a success. We also thank the Office of Naval Research for their generous support.

C. Chryssostomidis
K. Johansson

June 1999

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ENABLING THE SHIPBUILDING VIRTUAL ENTERPRISE

Richard W. Bolton, NIIP Consortium, Stamford, CT
Dr. Paul Horstmann, IBM, Poughkeepsie NY
Dr. Thomas Rando, General Dynamics Marine Systems, Groton CT

Introduction

The National Industrial Information Infrastructure Protocols (NIIP)[1] Consortium, in partnership with the shipbuilding operations at Electric Boat Corporation, Bath Iron Works, National Steel and Shipbuilding Company (NASSCO), Todd Pacific Shipyard, Newport News Shipbuilding, and Ingalls Shipbuilding is working jointly to establish Virtual Enterprises (VE's) encompassing the shipbuilding community. The US Shipbuilding VE is composed of customers, partners, subcontractors, and suppliers using National Industrial Information Infrastructure Protocols (NIIP) technology to enable electronic-based business interoperations that are transparent of the underlying processes and computing environments of the participants.

The establishment of a shipbuilding virtual enterprise capability will:

- Enable the implementation of Advanced Business Practices in requirements analysis, supplier relations, material procurement, resource management, and financial management by enabling information technology interoperation amongst shipyards and their integrated product teams.
- Enable Total Process Systems by establishing system-wide integrated design and production capabilities, thereby reducing the total time and cost of ship design and construction.

This effort is called the National Industrial Information Infrastructure Protocols (NIIP) for Shipbuilding Partners and Suppliers (SPARS) - "NIIP SPARS" Project. NIIP SPARS is funded by DARPA MARITECH to extend and enhance single-shipyard-oriented information technology to coordinate the interactions of the larger shipbuilding community, collectively referred to as the "*Shipbuilding Virtual Enterprise (SVE)*". Figure 1 shows that NIIP SPARS establishes information connectivity and process management by deploying **Virtual Enterprise Servers (VESs)** and **Virtual Enterprise Clients (VECs)** that provide common access points and interoperability services for all participating organizations. NIIP SPARS creates "sockets" for interconnecting organizational (shipyard-centric) infrastructures in a well-defined and controlled manner. The NIIP SPARS Project was launched October 1, 1997 and will conclude on September 30, 2000.

NIIP SPARS will provide state-of-the-art technology that is key to revitalizing the United States shipbuilding industry and increasing its share of the international shipbuilding market. In the mid-1970s, US shipbuilders produced, on average, twenty (20) large oceangoing commercial vessels per year; this production rate has been steadily decreasing, with fewer than twenty (20) commercial vessels

[1] The NIIP Consortium is a non profit joint research and development consortium founded in 1994 to develop interoperability protocols to enable the creation of industrial virtual enterprises. Please refer to www.niiip.org.

ordered from United States shipyards since 1982[2]. This decline in international market share has translated into an estimated loss of 180,000 jobs.

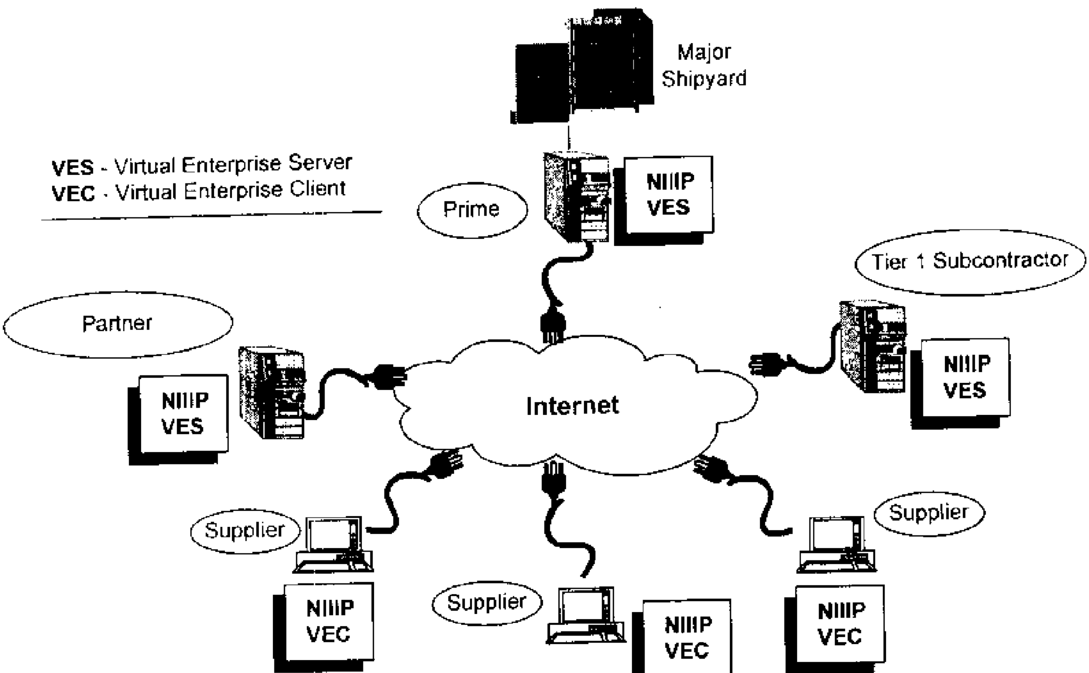

Figure 1. Shipbuilding Virtual Enterprise

To regain lost market share, United States shipbuilders must dramatically improve:

Customer interaction to be more responsive during conceptual design, have a better understanding of part availability and the configurations of standardized options, and exercise more control over construction costs and delivery dates.

Subcontractor interaction to increase competitive advantages by focusing on core competencies, increase cost efficiencies by relegating secondary competencies to specialized outsourcing agreements, and absorb sporadic workloads by having access to reserve production resources.

Supplier interaction to optimize subsystem costs by arranging long-term sourcing agreements, improve ship designs by establishing Integrated Product Teams (IPTs), and more efficiently utilize capital by minimizing the costs of storage facilities and part inventories.

NIIIP SPARS addresses these key requirements by establishing shipbuilding virtual enterprises that allow people to interact, applications to interoperate, and computing platforms to intercommunicate. More specifically, the NIIIP SPARS Project will create:

- **Virtual Enterprise Servers** (VESs) and **Virtual Enterprise Clients** (VECs) that will provide common computing platforms and affordable entry/access points for shipbuilding virtual enterprises. A common infrastructure is important because shipyards, subcontractors, and suppliers

[2] SCA, "International Shipbuilding Aid - Shipbuilding Aid Practices of the Top OECD Subsidizing Nations and Their Impacts on US Shipyards," Shipbuilders Council of America (SCA), Arlington, VA, 1993.

will participate in multiple projects both concurrently and over time and start-up costs for the creation of new shipbuilding teams are minimized.

- **Information Management**, including electronic data interchange (EDI), technical data interchange (TDI), and Product Data Management (PDM), that will enable users to directly access and share enterprise-wide information in real-time. Data is entered once by the originator and used many times throughout the shipbuilding virtual enterprise without the penalties of reentering data. Change and configuration control are managed in real-time; information remains current and consistent across the SVE.
- **Process Management**, including session, and workflow that will enable distributed shipbuilding specification, design, assembly, and repair. An overall integrated/interoperable process and schedule is maintained throughout the shipbuilding virtual enterprise.
- **Mobile Computer-Aided Assembly** to merge the information space describing the assembly of a large vessel with the workspace of technicians performing the assembly. Enterprise-wide information is brought down to the deckplates where it is needed.

NIIP SPARS Innovations

The NIIP SPARS project is innovative in the manner in which it *facilitates* and *accelerates* the implementation of shipbuilding virtual enterprises for United States shipyards by:

- Establishing shipyards as virtual enterprise gateways to provide **near-turnkey shipbuilding business processes** to their supply chains, thus enabling product teams to cost effectively work as integrated units.
- Establishing **interoperability mechanisms** to link together heterogeneous computer, application, and data systems of different companies to enable rapid communication, accurate monitoring, and responsive control of shipyard activities ranging from personnel administration to manufacturing logistics.
- Providing secure and easy-to-use Internet-based on-line access to supplier information (qualifications and product) by prime contractors and prime contractor information (solicitation and procurement) by suppliers.
- Providing accurate and cost-effective sharing of design information using MARITECH and NIIP sponsored part representation, translation, and exchange technology.
- Establishing proof-of-production feasibility of mobile computer-aided assembly and disassembly.

NIIP SPARS Impacts

The NIIP SPARS project has **pervasive impact** on advancing the United States defense and commercial shipbuilding industry because:

- NIIP SPARS facilitates partnering to enable United States shipyards to establish strategic alliances and joint ventures to aggressively pursue new international business engagements and production deployment.
- NIIP SPARS allows shipyards to more easily reconfigure their resources to address production of high-mix, low-volume vessels and, consequently, pursue **niche** or **specialty markets** that are easier

to penetrate than the larger markets of bulk carriers, tankers, and container ships where international competition is well entrenched.

- NIIIP SPARS is an advanced technology initiative, recognizing that new ship designs are not readily patentable and, thus establishing and protecting market share requires investing in technology to continuing improve cost and performance.
- NIIIP SPARS is based on an open information system architecture supported by leading commercial application and system vendors:
    - NIIIP SPARS is not point-to-point integration;
    - NIIIP SPARS is not a "one-off project
    - NIIIP SPARS is not proprietary.
- NIIIP SPARS promotes and leverages procurement, qualification, and part information standards using Accredited Standards Committee (ASC) standards for electronic data interchange (EDI), International Standards Organization (ISO) standards for technical data interchange (TDI), and Marine Machinery Association (MMA) standards for part ontologies/libraries.
- NIIIP SPARS has **minimal impact** on organizational information systems; shipyards will continue to use *existing* processes and practices. Bridges are used to link to existing computing environments; applications are "wrapped" to instantiate appropriate NIII Protocols.

NIIIP SPARS Project Participants	
Member Organizations	**Roles/Contributions**
Electric Boat	End-User
Bath Iron Works	End-User
Todd Pacific Shipyard	End-User
National Steel and Shipbuilding Company (NASSCO)	End-User
Newport News Shipbuilding	End-User
Ingalls Shipyards	End User
Allied Signal Submarine Systems	Supplier
Marine Machinery Association (MMA)	Suppliers
International Business Machines (IBM)	Technology Provider
STEP Tools, Inc. *Technical Approach*	Technology Provider
International TechneGroup Inc. (ITI)	Technology Provider
Carnegie Mellon University	Technology Provider

Technical Approach

To compete in international shipbuilding markets, the United States shipyards must decrease production time. On average, the design-through-construction cycle of an ocean-going vessel is 1.5 to 2 years in the United States and 1 to 1.5 years in Asia countries (South Korea and Japan)[3]. One of the major factors influencing ship production time is the ability to rapidly bring together worldwide **integrated product teams** and to responsively deploy the teams to pursue international business opportunities, as illustrated in Figure 2.

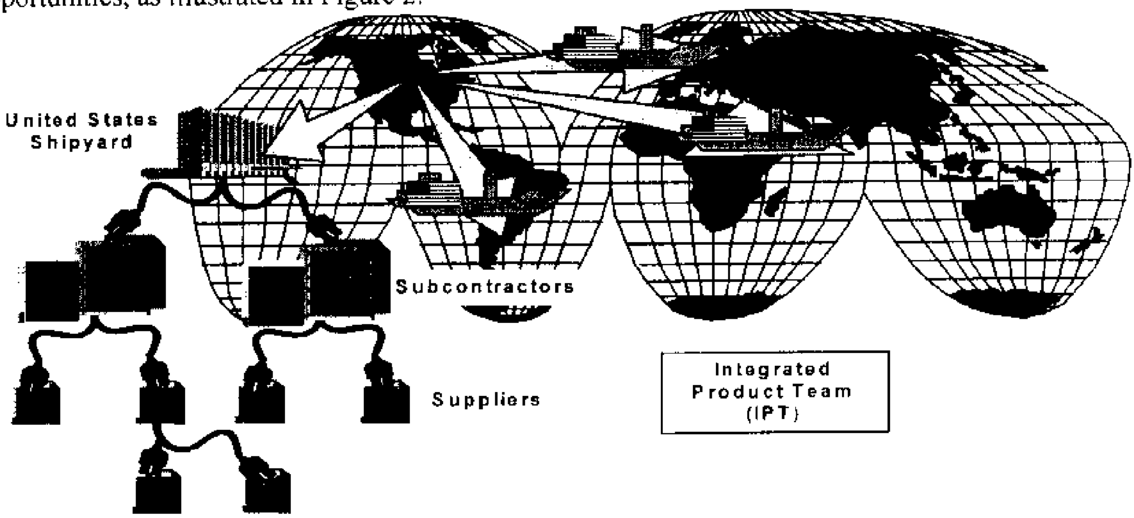

Figure 2. Global Deployment of Integrated Product Teams

The challenges of assembling and deploying integrated product teams worldwide are not unique to the shipbuilding industry. Increasing international competitive pressures are motivating all industrial corporations to continually improve return on assets and reduce working capital. In addition to improving internal production efficiency efforts, corporations are turning to external factors, such as subcontractors and suppliers, to achieve new cost savings and higher profit margins. Ship construction and repair are assembly-intensive operations that involve high levels of logistics; supplier part production can account for approximately 50 percent or more of total production costs. Improving Integrated Product Team (IPT) management can help corporations better understand their production enterprises and these insights can be used to optimize processes and products. Overall production strategies can be reengineered and streamlined to make optimum use of in-house skills and out-sourcing resources. Thus, integrated product teams are emerging as a pivotal opportunity for gaining new competitive advantages and markedly improving overall production costs.

A key element to improving the efficiency of shipbuilding product teams is to improve their integration; organizations operating within a product team need to "talk to each other[4]." The NIIP SPARS project presents a comprehensive solution to significantly improve product team integration by organizing and instantiating the product team as a virtual enterprise. Virtual enterprise technology

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[3] Kempfer, L., "Competitive Shipbuilding," Computer Aided Engineering, Vol. 15, No. 7, July 1996, pg. 8-9.

[4] National Research Council, *Shipbuilding Technology and Education*, Washinton DC, 1996, pg. 2.

enables electronic-based business engagements that are transparent of the underlying processes. computing environments, and data structures of the participants. In other words, a virtual enterprise supports organizational interoperability within a controlled context, which precisely addresses the requirements for efficient product team integration.

The **organizational interoperability** ("Corporate Plug-and-Play") focus of NIIP SPARS, illustrated in Figure 3, is aligned with current industry directions, as the most dominant trend in state-of-the-art product team management is the move toward fully integrated systems[5].

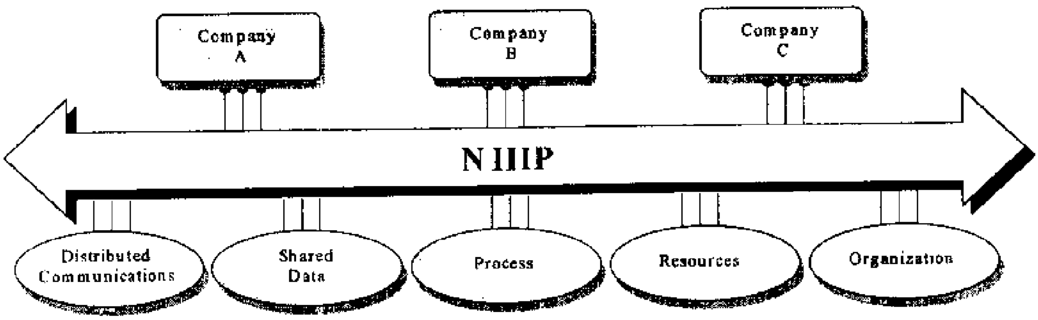

Figure 3. NIIP Organizational Interoperability

Companies are interested in replacing duplicate and incompatible information processing systems with consolidated and common computing platforms and information processing environments.

The **infrastructure** focus of NIIP SPARS is also aligned with current industry directions, as managing product teams cannot be accomplished by a single closed-form, analytic optimization process; this is too simplistic of an approach[6]. Product teams are too complex and involve too many independent and pertinent variables. Managing product teams requires the collective efforts of several individuals/tools, which, in turn, requires complete visibility into the status of all participants and their work. Tools provide potential optimization capabilities, but the "fuel" that drives these tools is information - getting the right data at the right time. NIIP SPARS establishes information sharing throughout a shipbuilding virtual enterprise by using the National Industrial Information Infrastructure Protocols that are based on open, widely endorsed industry standards. Moreover, the standards are interlocked within a reference architecture that accommodates diversity, i.e., heterogeneous environments.

NIIP SPARS enables advanced shipbuilding by realizing integrated product teams as instantiations of virtual enterprises, linking management, engineering, customers, and suppliers. The high level architecture of NIIP SPARS is shown in Figure 4. The following paragraphs discuss general features; individual services and components are discussed in detail in subsequent sections.

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[5] Macleod, M., "What's New in Supply Chain Software", Logistics, June 1994, P 22-23.

[6] Arntzen, B., Brown, G., Harrison, T., and Trafton, L., "Global Supply Chain Management at Digital Equipment Corporation," Interfaces, Vol. 25, No. 1, January-February 1995, pp. 69-93.

To describe the high level architecture of NIIIP SPARS, it is convenient to view the NIIP SPARS system as an "information broker." To dramatically improve shipbuilding integrated product team and supply chain efficiency, the role of the brokers must evolve into the computer networks linking the producers and consumers; this is precisely the role of NIIIP SPARS. NIIIP SPARS serves as an intermediary broker to enable prime contractors to quickly and easily integrate their team members into a shipbuilding virtual enterprise that appears like a custom and private electronic commerce network. In this brokering role, the NIIIP SPARS-VES sits largely outside organizational firewalls as a non-invasive buffer, but can, at the discretion of an organization, readily extend into an organization's information processing systems via NIIIP component-oriented interoperability technology. Figure4 shows that NIIIP component-oriented interoperability is modular to accommodate a wide variety of information technology, including distributed object systems (Object Request Broker (ORB); Enterprise JavaBeans(EJB), and Distributed Component Object Model (DCOM)), distributed file systems (Network File System (NFS) and Andrew File System (AFS)), and software environments (Java). In this manner, NIIIP SPARS makes no assumptions about organizational information systems. nor the desired degree of product team integration and management. Each shipyard will likely pursue unique and tailored information brokering applications of NIIIP SPARS, ranging from highly empowered emissaries to more restricted proxies.

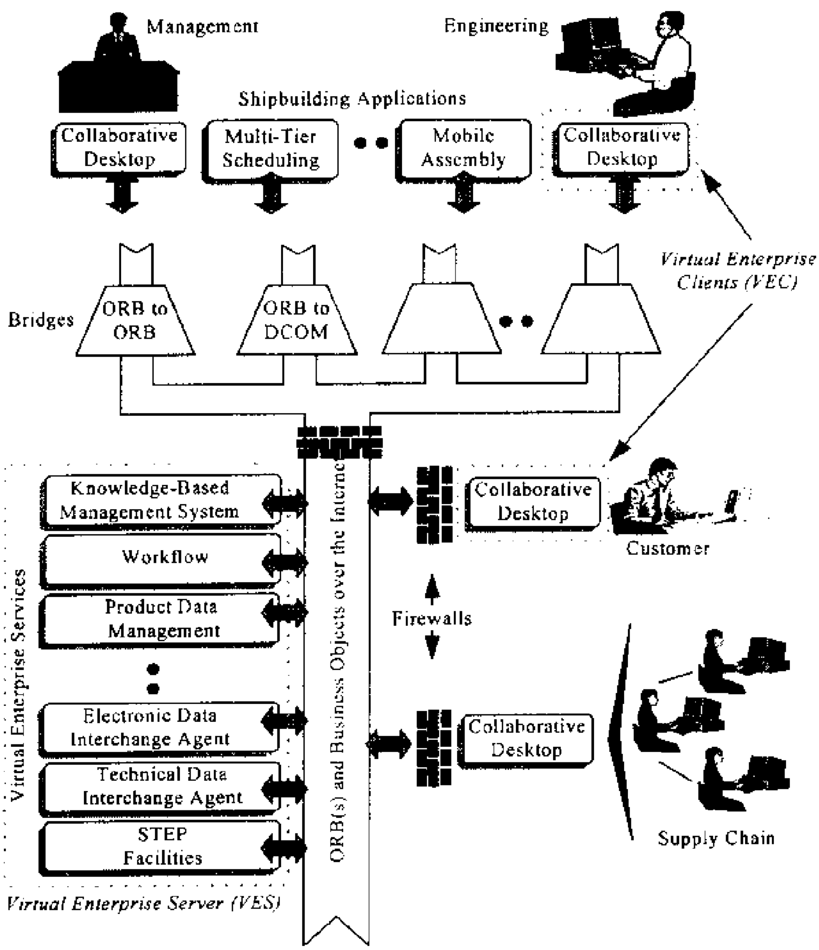

Figure 4. High Level Architecture of NIIP SPARS

NIIP SPARS is **extensible** because the underlying NIIP Reference Architecture is mediated, rather than integrated. The mediated architecture recognizes the practical reality that wide area networks of organizations cooperating within a product team involve a diverse and continuously changing mix of old and new applications and computing environments. Diversity is accommodated by providing *wrappers* and *bridges*; for instance, Figure shows bridges linking a Virtual Enterprise Server to ORB and DCOM organizational computing environments. Supporting DCOM enables shipyards using low-cost, desktop-based personal computing environments to be readily integrated into product teams. NIIP SPARS is **broadly implementable** because the implementation is client/server oriented, as shown in Figure 5.

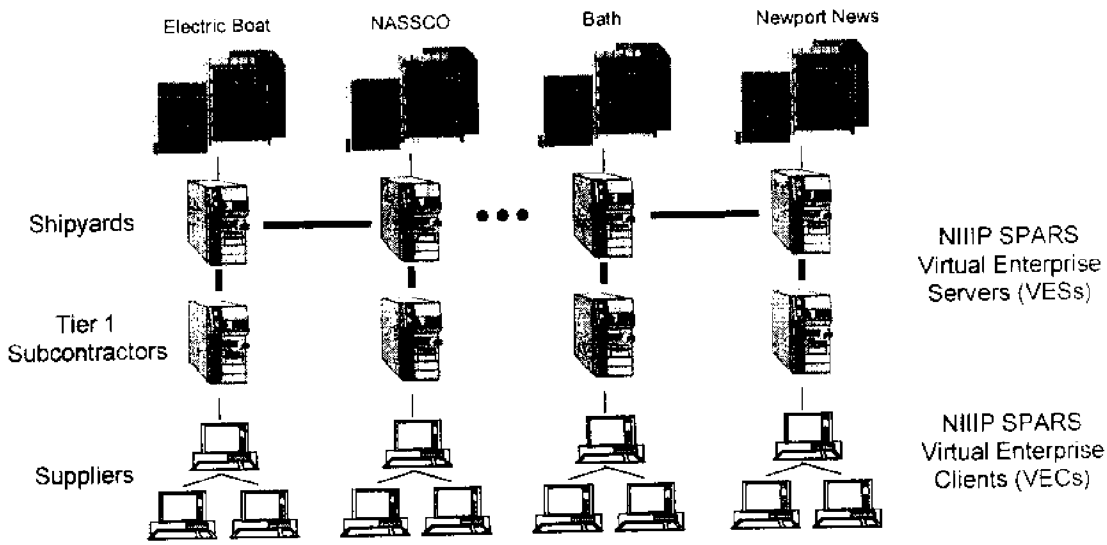

Figure 5 . NIIP SPARS Virtual Enterprise Client/Server Implementation

Such an approach provides a "*near-turnkey*" integrated product team management solution: the server supports pre-packaged core virtual enterprise information and process management features and the client supports an easy-to-use, "light-weight" interface. The heavy lines in

Figure5 denote server/server communication and are object-oriented transactions. The lighter lines denote client/server communication and are file-oriented transactions. This physical partitioning optimizes performance/cost tradeoffs by offering extensive integrated product team management for prime contractors and economical registration and participation for customers, partners, subcontractors, and suppliers. Companies will be more disposed to implement NIIP SPARS integrated product team management for advanced shipbuilding production because it can be delivered as a **solution** rather than a "do-it-yourself toolkit."

NIIP SPARS is **scaleable** because the architecture is object-oriented. The object-oriented architecture supports partitioned, modular interfaces that promote the development of "plug-and-play", reusable software components. NIIP SPARS distributed object network is based on Java, Enterprise JavaBeans (EJB) and CORBA, a computable object modeling paradigm that decomposes traditionally large corporate applications into smaller, reusable functions that can be exploited by new visual software engineering practices to quickly compose custom shipbuilding applications[7].

Solution Architecture

The SPARS Alpha Architecture represents the initial prototype instantiation of NIIIP SPARS concepts that will tested in 1999 at participating shipyards.

The SPARS solution is a service point, called a Virtual Enterprise Server (VES), providing access and services to shipyards and suppliers. The VES is a logical entity made up of a collection of servers which may be installed on one or more machines, depending on the individual requirements of the shipyard and its suppliers, and the platforms that the required software is available on. It is anticipated that the VES may be in an extra-net outside of a shipyard firewall.

The SPARS Alpha Architecture contains the following set of major elements:

- Desktop (Tier 1) - Provides access to the SPARS VES from within shipyards and suppliers. The desktop contains objects that represent access control, documents, folders, workflow activities, and other items within the shipyard processes. The Desktop is a first tier element. The objects of the desktop interact with the EJB server objects of the second tier via RMI.

- Web Server (Tier 2/3) - Provides the Web interface to the SPARS VES for initial loading of the desktop HTML and Java, and provides the portal through which Java Servlets and underlying applications are accessed as needed within the VES infrastructure.

- Server EJBs (Tier 2) - Provide services (*Workflow* - process control, *People Directory* - people/group/role information query/manipulation, *Document Directory* - document information query/manipulation, *Document Vault* - document management) for operations of the VES. These server EJBs are second tier elements. The EJBs interact with third tier implementations (typically COTS products providing underlying functionality) either via CORBA object calls (if within the VES) or via HTTP messages (within the VES or to third tier implementations outside the VES, for example within a shipyard). The use of HTTP messaging facilitates navigation of firewalls between the VES and the shipyard. The HTTP messages are handled directly by the implementation or via a web server/servlet interface in front of the application.

- Implementations (Tier 2/3) - Implementations (usually COTS products) provide underlying functions in support of the server EJBs. For Alpha these include a workflow system, document vault, and LDAP directories. For any given shipyard, some implementations may reside within the shipyard firewall while others reside inside the VES.

It should be noted that each VES instantiation may contain one or more logical or physical instances of the above elements.

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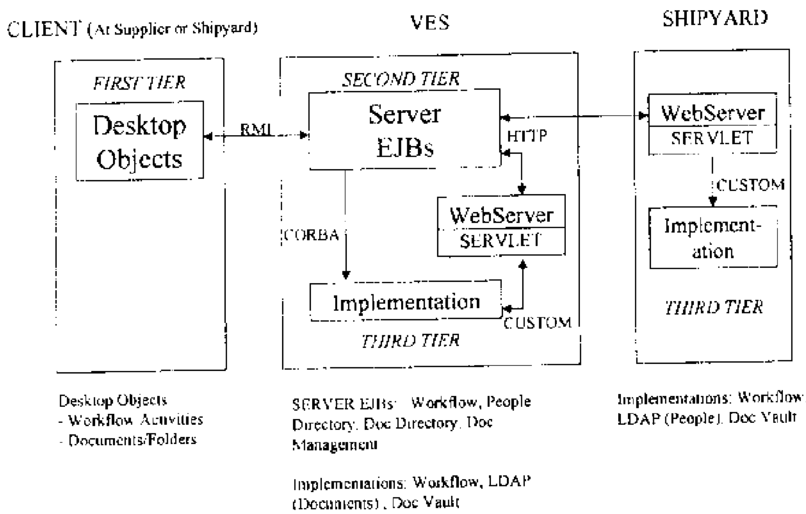
[7] Kao, C., Li, D., Wu, C., Lyu, J., Shaw, H., "Planning for Automation for Shipyards - An Illustrative Study," Computers in Industry, Vol 27., 1995, pg. 33-41.

SPARS Alpha Architecture
and candidate element examples



NIIP SPARS Collaborative Desktop

The Collaborative Desktop is the user's window into the shipbuilding virtual enterprise that transparently extends beyond the physical boundaries of local facilities and resources. The Collaborative Desktop presents to the user the integrated product team services authorized for that user; users include prime contractors, subcontractors, suppliers, customers, and trading partners. Resources are accessed. Organizational policies and production processes are enacted. Applications are invoked. Applications may be end-user tools or other NIIP SPARS components that, in turn, invoke end-user tools. As an example of the latter, the Workflow component may be invoked, which, in turn, may invoke the Technical Data Interchange (TDI) Agent to retrieve and translate engineering data for an application. The Collaborative Desktop can be specialized to accommodate corporate policies and personal preferences.

The Collaborative Desktop provides for visualizing and operating the entire integrated product team, hiding the distributed nature of the supported services and participants.

The Collaborative Desktop uses **World-Wide-Web** (WWW) technology and associated browser interfaces to organize a complex integrated product team as a conceptually unified development/demand network. Such a network provides dynamic and adaptable information connectivity required to support global shipbuilding ventures.

The Collaborative Desktop also uses **Internet** technology to provide open, broadly available, and economical wide area network communication. Internet communication protocols are public and widely endorsed by the general computing industry.

Finally, the Collaborative Desktop uses **Java** technology for exchanging programs or computable objects. Downloadable computable objects, such as Java applets, allow servers to marshal, route, reinstantiate, and execute objects on clients and vice versa. Java applet execution is platform independent because applets are interpreted by an underlying "Java Virtual Machine" that sets on top of host platforms. Java presents new opportunities for interactions and integration between companies in a supply chain. When team members need to work with new information or wish to use a new application, the necessary code can be quickly and automatically distributed to avoid interrupting overall production. Such an approach has the advantages of local versus remote execution of code, and the ability to more efficiently transfer high-level representations of objects that are rendered locally rather than transferring low-level presentation data that is computed remotely. Java can also enable intelligent supplier parts and libraries; computable parts can invoke additional applications to render, analyze, or modify the specifications. Finally, Java enables service brokering within supply chains, as suppliers can offer their products and services on-line as portfolios of horizontally and vertically organized applets, also called "Java widgets."

NIIP SPARS Object Access and Transport

NIIP SPARS Object Access and Transport provides the application-level interoperability technology to:

- Build Virtual Enterprise Servers (VESs),
- Tie the Virtual Enterprise Servers (VESs) back into their respective parent organizations, and
- Link the Virtual Enterprise Servers (VESs) together to form a shipbuilding virtual enterprise.

Virtual Enterprise Servers are optimized configurations of the NIIP Reference Architecture and, as such, use distributed object network technology. An object can be a simple subroutine, a program, or collection of programs constituting a major software system. Both static and dynamic object service invocations are supported; dynamic object service invocations allow the discovery of new object services, or even new objects. Constructing object communications at runtime enables NIIP SPARS to accommodate shipbuilding virtual enterprise changes, such as new participants or new applications, during operation.

NIIP SPARS Information Management

NIIP SPARS Information Management provides the ability to share information throughout an entire shipbuilding virtual enterprise. Sharing information involves storage and exchange. Storing information within a shipbuilding virtual enterprise involves Product Data Management. Exchanging information within a shipbuilding virtual enterprise involves Electronic Data Interchange and Technical Data Interchange.

Product Data Management (PDM) provides controlled access to persistent data, optimized for product-oriented Bill-of-Material (BOM) structures. Query and retrieval are content and context based. Configuration and version control, respectively, support data modification and status upgrade across levels of security, quality and/or integrity. Product Data Management also operates across wide area network organizational gateways, commonly called "firewalls." Firewalls interject intermediary computers between users or applications inside an organization and the larger environment accessible via the wide area network to control information access and services. Commercial firewalls generally act as "information diodes" by allowing "out-going" actions by an organization accessing external wide area network resources, but limiting or disallowing "incoming" actions by an external user accessing an organization's internal resources. In other words, firewalls typically permit users within an organization to "pull" (retrieve) information from a wide area network, but restrict users on the wide area network from "pushing" (sending) information into an organization. Product Data Management across Internet firewalls is supported by using the "SOCKS" versions of the Internet protocols[8] and a "post-and-pickup" exchange procedure. A post-and-pickup exchange procedure transfers information between organizations by first posting the information to a neutral repository (Virtual Enterprise Server) connected to the Internet and then notifying intended recipients. The recipients then pull the information in through their respective organizational firewalls to complete the transferal.

Electronic Data Interchange (EDI) provides standards for communicating business-oriented transactions. Typically, a business application, such as accounting, generates a transaction, such as an invoice. Since the transaction is usually in the proprietary format of the particular business application, there is the need to translate the transaction into a standard, interoperable format amenable to electronic transmission and processing. EDI standards (ASC X12) and associated software provide such a capability. Applicable EDI Transaction Sets include X12-840, X12-841, X12-843, X12-850, and X12-997. To interface to the Collaborative Desktop, NIIIP SPARS EDI also provides translation between ASC X12 transaction set format and the World-Wide-Web (WWW) Hyper Text Markup Language (HTML) format.

Technical Data Interchange NIIIP SPARS Information Management leverages Standard for Exchange of Product Model Data (**STEP**) technology to provide uniform part data representation, low-cost distributed part library management, and fine-grain part data application interface interoperation. Uniform part data representation is supported by providing the ability to capture, annotate, and convert 2-dimensional/3-dimensional part design information (STEP AP 203 Configuration Controlled Design and AP 202 Associative Drafting) to feature and process manufacturing information (STEP AP 213 Process Plans for Numerical Control and AP 224 Form Features for Numerical Control). This part data representation capability will be derived from the Application Protocols (APs) developed by the Navy/Industry Digital Data Exchange Standards Committee (NIDDESC) that provide standard descriptions of product model data for incorporation into the International Standards Organization (ISO) Standard. Translation between these STEP Application Protocols (APs) and proprietary computer-aided design/manufacturing systems will leverage MariSTEP technology (AP 215, AP 216, AP 217, AP 218).

NIIP SPARS Process Management

Establishing the ability to communicate and share information throughout an entire integrated product team is necessary, but not sufficient, to realize advanced shipbuilding. In other words, in addition to enabling communication between applications X and Y, the conditions under which application X may communicate with application Y and the expected nature of the transaction must also be defined. NIIIP SPARS Process Management provides a controlled context for conducting integrated product team operations. NIIIP SPARS provides interoperability within a higher-level context that recognizes

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[8] Cheswick, W. and Bellovin, S., *Firewalls and Internet Security*, Addison Wesley, 1994.

participants and expected actions. NIIP SPARS Process Management consists of a hierarchy of control contexts, involving **session, workflow**, and **application** management.

Session management provides administrative control for each participant of the integrated product team, i.e., virtual enterprise. Session management defines the concepts of users, groups, roles, and workspaces to specify user log-in and access privileges. The state of a user's account is managed by servicing synchronous and asynchronous events and transactions. User-directed commands and system directed messages are recorded. Session management services work (task) requests by invoking workflow management.

Workflow management controls the actions required to accomplish a task. Workflow management defines integrated product team processes and associated personnel activities in a computable form that enables enactment and enforcement. Workflow provides supervisory capabilities to assist in coordinating people and resources, initiating actions, and monitoring task progress/completion. Workflow management also maintains an audit trail of runtime activities: this information provides valuable metrics for continuous process improvement. Workflow management services software innovation requests by invoking application management.

Application management, also called tool management, provides support for executing software programs. Applications are registered and invoked, adhering to proper authorization controls and licensing procedures. Required data is accessed, locked, and, if necessary, translated into target format(s). Also, software program suspension, activation, and error recovery are provided.

NIIP SPARS Virtual Enterprise Management

NIIP SPARS Virtual Enterprise Management encodes the information that collectively defines what constitutes a shipbuilding virtual enterprise. Prime contractors, subcontractors, partners, suppliers, and customers are registered to define participants and associated responsibilities and authorities. Applications are also registered to define resources and associated capabilities, constraints, and dependencies. Participants and resources collectively form the "state" of an integrated product team, also more generally called the virtual enterprise object.

State information is used to support the efficiency and integrity of forming, operating, and dissolving shipbuilding virtual enterprises. State information also supports understanding what aspects of a shipbuilding virtual enterprise should be changed to accommodate new requirements, such as integrating new applications. Having such a single repository for integrated product team organizational information alleviates the need for each participant or application to keep private copies of global configuration information.

Shipbuilding virtual enterprise state information is encoded as rules and managed by a rules service. Rules support declarative-style information modeling that avoids the complexities of procedural-style information modeling and facilitates upgrades or changes. Also, rules are readily interpreted by conventional computer parsing technology. Finally, rules can encode "active state" information, in which actions are initiated under certain conditions to update state information, prohibit illegal transactions, or enforce business policies.

NIIP SPARS Mediated Application Interoperability

NIIP SPARS Mediated Application Interoperability couples select applications into a shipbuilding virtual enterprise. Integrated product team application suites will generally differ, depending on the participants and the level of integration, i.e., how extensively the participants desire the product team to be connected into their respective operations. Major classes of applications impacting integrated product team operations include computer-aided design (CAD), enterprise resource planning (ERP), and product data management (PDM).

NIIP SPARS enables interoperability of both old (legacy) and new applications. NIIP SPARS interoperability is permissive and makes no assumptions about prerequisite access and knowledge of the internal workings of applications. Indeed, most commercial off-the-shelf (COTS) products do not provide any visibility into their internal, proprietary technology. NIIP SPARS interoperability is based on external, application-neutral interfaces. New applications can be upgraded to directly support the interfaces; old applications can be "wrapped" to indirectly support the interfaces.

NIIP SPARS supports syntactic and semantic application interoperability. Syntactic interoperability is achieved by object encapsulation and translation. Semantic interoperability is achieved by object encapsulation and mediation. Mediation resolves local schemas into a global schema that defines a shared ontology for operating the integrated product team. Syntactic and semantic interoperability allows product team participants to retain a degree of autonomy and for applications to "speak different dialects." Thus, all participants do not have to agree on a single object representation schema before initiating a shipbuilding virtual enterprise.

NIIP SPARS Mobile Computer-Aided Assembly

Mobile Computer-Aided Assembly addresses another key integrated product team operation: merging the information space describing the assembly of a large ship with the workspace of a technician in the shipyard performing the assembly. Shipbuilding is an assembly intensive process: constructing, outfitting, and repairing activities involve scheduling and coordinating thousands of items. Consequently, material handling within a geographically dispersed shipyard is a major cost driver of ship construction. NIIP SPARS Mobile Computer-Aided Assembly reduces material handling costs by streamlining parts flows and developing more efficient building strategies and construction sequences.

NIIP SPARS Mobile Computer-Aided Assembly uses light-weight mobile computers integrating wireless telecommunications, real-time software, and battery-operated low-power electronics worn by technicians to provide automatic, portable access to shipbuilding assembly information. Visualization is provided by a small head-mounted eye display. Bills of Material are transformed into construction sequences; the viability of required construction procedures are confirmed, including tools, fixtures, and human access. Human access addresses whether a technician has appropriate visibility, reach, grasp, and dexterity to execute construction procedures. Position and motion sensing enables information to be accumulated as the technician interacts with and modifies the environment, thereby providing data acquisition for inspection checklists and user feedback for trouble-shooting procedures.

Mobile Computer-Aided Assembly for advanced shipbuilding is another significant technical challenge in NIIIP SPARS, involving the development and integration of technologies not presently established. To mitigate develop risks, the development schedule defines several interim milestones for establishing an initial proof-of-production feasibility and assessing the benefits of continued work.

SUMMARY

The NIIIP SPARS Project will provide the US Shipbuilding Community with an information infrastructure that will facilitate significant advances in timeliness and productivity.

NIIIP SPARS is built upon an open architecture and uses industry standards to facilitate wide acceptance by both shipyards, their suppliers, and by the information technology industry. Information will be entered once and used multiple times by the participants in the shipbuilding supply chain. Consistent, accurate and timely information will be widely available. Redundant information can be eliminated. Errors due to manual data re-entry can be eliminated. Cycle time can be reduced.

THE INDUSTRY-WIDE INTRANET FOR SHIPS AND OCEAN ENGINEERING

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Introduction

The emerging information and communication technologies are rapidly changing the industrial environment. The shipbuilding business processes are changing too. Globalization of markets and production, decentralized work, moving toward the flexible organization, growing use of outside services are some of these realities. Now the information and communication technology is not merely a tool to strengthen the competitiveness but a strategy to survive in the near future.

Since the introduction of management information system (MIS) and NC technology for the manufacturing system in the late 70's, the major Korean shipbuilders have made a lot of investments on computerization and automation of the design and manufacturing processes. Drawing boards have been replaced by CAD workstations in the 80's, the efforts to integrate design and production process with information are being proceeded on the basis of 3D CAD product model in the 90's. But these efforts are being made only by large shipbuilding companies independently. In 1995, the Korea Shipbuilding Research Association (KSRA) planned a five-year project, Computer Integrated Shipbuilding System, not only for the productivity but also for cooperative attitude in the shipbuilding community.

From the feasibility study of the project, the conceptual model with some topics has been defined as shown in Figure 1. The project started in December 1995. Four major shipyards and KRISO (Korea Research Institute of Ships and Ocean Engineering) lead each topic.

Ksnet (Korea Shipbuilders' Network) is one of the initiatives coordinated by KRISO. The goal of this study is to establish the information infrastructure for Korean shipbuilding community to communicate and share information. Also KSnet is aimed to build a framework for the implementation of internet-based collaborative engineering and electronic commerce.

The Industry Wide Intranet for Shipbuilding

Conception

With the growth of the Internet, the construction of company-wide Intranet is brisk. The essential difference between Internet and Intranet is the range of information sharing and exchange. In Internet, the exchange of information is open to external world, but it is closed in Intranet. Internet provides WWW (World Wide Web) service on the WAN (Wide Area Network) but Intranet provides CWW (Company Wide Web) service on the LAN (Local Area Network). The advantage of Intranet is sharing of information between heterogeneous platform while protected from public access.

By using the Internet-based technology, we can establish a new engineering environment, called as Industry Wide Web (IWW), to realize the collaborative engineering and the electronic commerce inside the shipbuilding community (Figure 2).

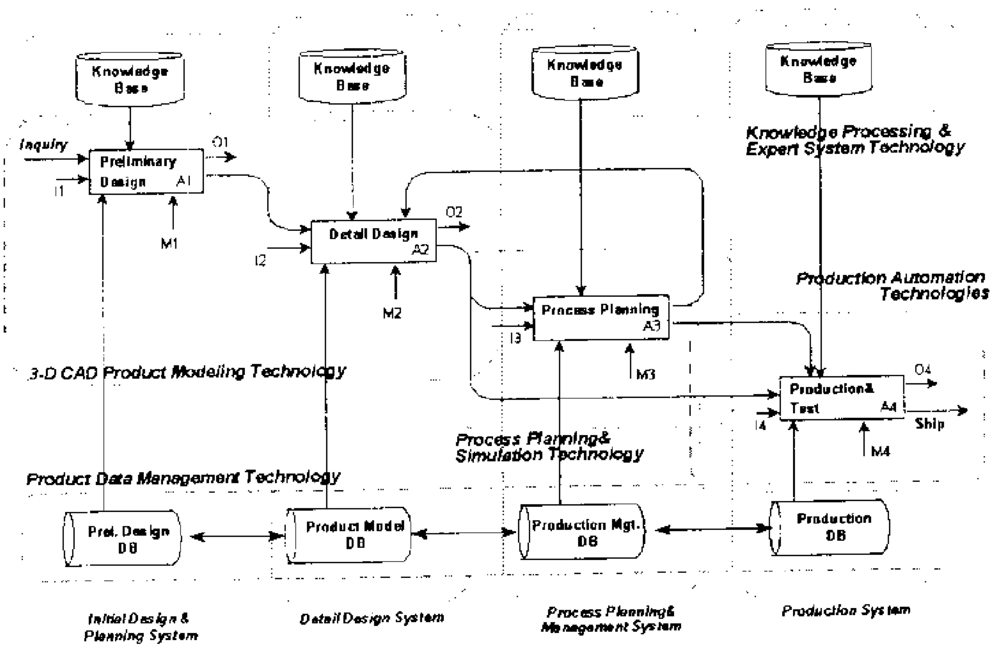

Figure 1. Conceptual Model of Computer Integrated Shipbuilding System

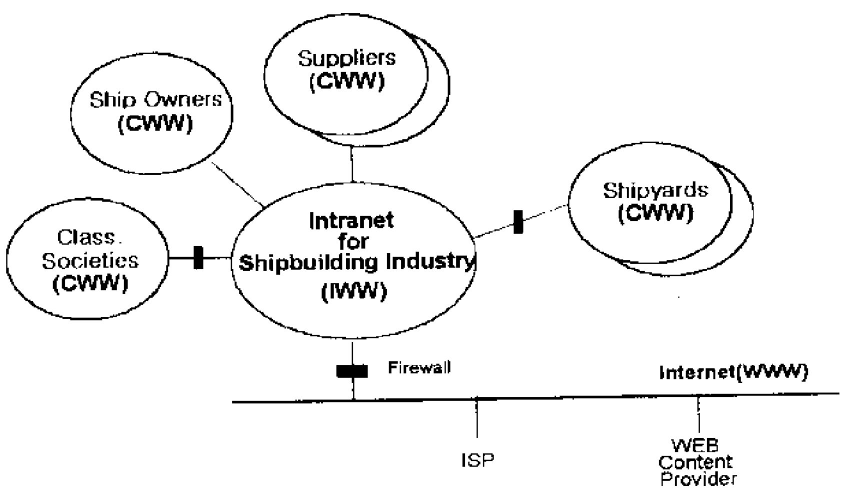

Figure 2. Concept of Industry Wide Intranet for Shipbuilding

Korean Shipbuilders' Network(KSnet)

Within the Korean shipbuilding community, there are about 120 shipyards including small and medium sized ones, about 20 consulting companies, more than 200 marine equipment suppliers. 20 shipping companies, eight classification societies including Korea Register of Shipping (KR), research institutes, and universities (Figure 3).

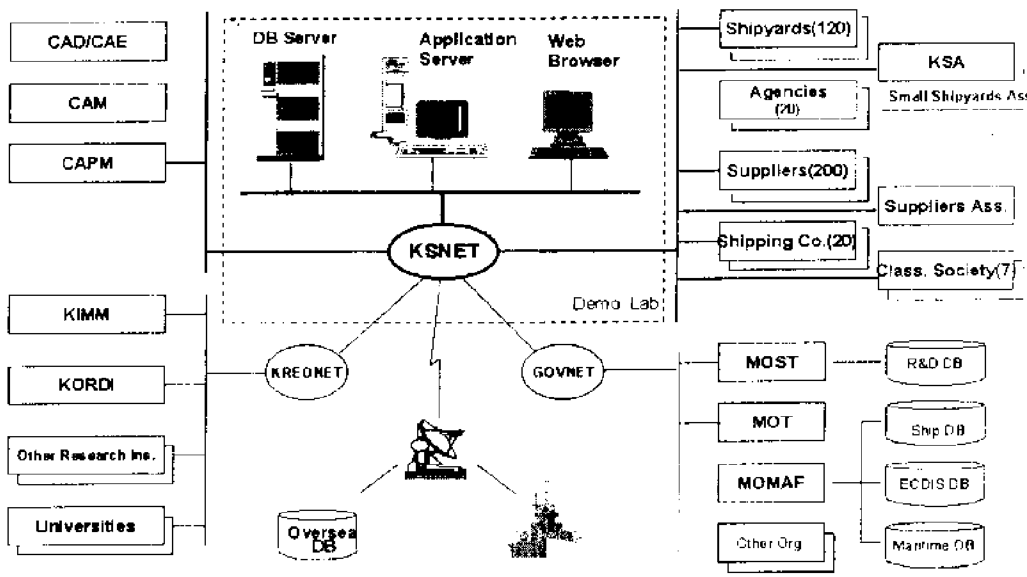

Figure 3. Layout of Korea Shipbuilding Network (KSnet)

KSnet provides communication services, information services, education services, and engineering service as follows.

- Communication Service:

This service provides many facilities such as electronic bulletin board system (BBS), mailing list, and electronic data exchange. They enable to share and exchange the technical information between related partners. Communication service is a backbone for the electronic commerce and collaborative work.

- Information Service:

This service provides on-line information such as industry trends, news, events, R&D projects, and links to related web sites.

- Education Services:

This is a kind of education-on-demand service. Education-on-demand can overcome the time and location limitations of on-site education. This service can be useful and practical for small and medium sized shipyards and marine equipment makers, which have financial and technical difficulties.

- Engineering Services:

The collaborative engineering center can be implemented on the basis of KSnet. This center can provide engineering services for organizations and companies that lack technical expertise

Chunghaejin: The Prototype System of KSnet

Chunghaejin is web-based shipbuilding information service system, designed for realizing the concept of KSnet, and for validation and accommodation of evolving Internet and Intranet technologies into shipbuilding system. As shown in Figure 4, *Chunghaejin* consists of seven modules, KS-Network, KS-Library, KS-News & Event, KS-R&D, KS-University, KS-Museum, and KS-Mart as follows:

- KS-Network:

KS-Network aims to provide an environment and devices for communication and collaboration within Korean shipbuilding community. Especially the utilities for various Small Interest Group like study circles are provided. Through this module the users can link to shipyards, marine equipment suppliers, shipping companies, government organizations, classification societies, universities, and other related sites. Currently, over than 200 sites are linked.

- KS-News/Event:

This module aims at cyber broadcasting center which provides useful information for the maritime domain. It also provides a variety of information such as policies related to ships and ocean engineering, international market trends, academic events, and exhibitions. The utilities, uploading, archiving, and searching of news and events are available for the users.

- KS-Library:

This module facilitates sharing of technical information and aims at a virtual library that allows users to search, register, and utilize all the information. Currently, it provides a technical information service of the Korean maritime library and public technical libraries.

- KS-R&D:

This module provides information about R&D projects and also aims to establish virtual laboratory for collaborative research project. Currently, it has links to related R&D projects. It is used for managing the KSRA projects.

- KS-University:

This system aims at a cyber university specialized for ship and ocean engineering technology education with concept of education-on-demand (EOD). Currently, it provides materials for the small and medium-size shipyards and the dislocated education service program is available.

- KS-Mart:

This module aims to build a cyber mall, which provides digital environment for collaborative work and electronic data interchange (EDI) between shipyard and marine equipment suppliers. Currently, the database for standard equipment of the Korea Shipbuilders Association (KSA) is available to the ship designers and equipment manufacturers.

• <u>KS-Museum</u>:
It aims at the cyber museum of ships and ocean engineering. At the moment this site provides the general information, for example, history of ships, links to historical sites and public museums.

KSnet is a user driven system directly operated and managed by users, so we mainly develop utilities that makes it easier to use KSnet rather than to provide contents. For example, KSRA provides technical trends, and organizers directly register the event information. The entire file formats, such as HTML, SGML, VRML, and AVI are available. Every module provides searching facility and the users can download data. Figure 5 shows the title page of *Chunghaejin*.

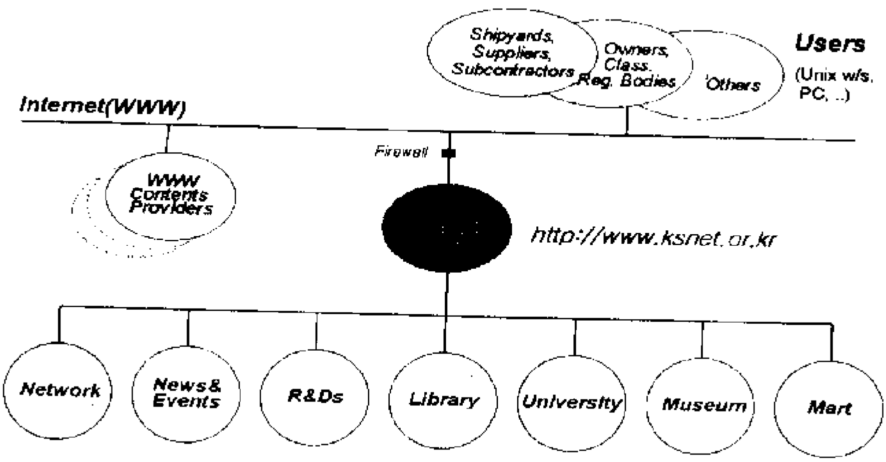

Figure 4. Configuration of the Shipbuilding Information System (*Chunghaejin*)

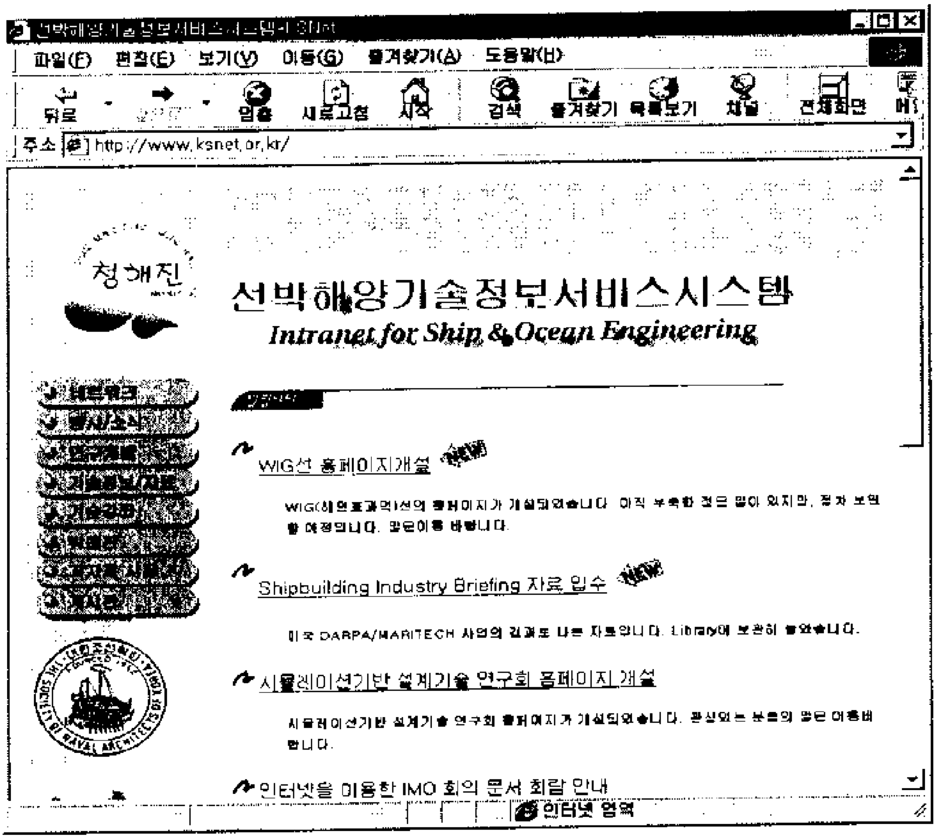

Figure 5. Title Page of *Chunghaejin*

KSnet-Based Collaborative Engineering

Background

The quantity of product information related to development and production increases in proportion as an enterprise enlarges and products are diversified. In order to prevent conflicts and to improve productivity, knowledge sharing among departments and companies through electronic communication are important. In this viewpoint, the information sharing to generate and maintain the product information becomes an important issue for collaboration.

As shipbuilding industries need close cooperation among the related companies such as shipbuilding company, ship owners, classification society, marine equipment suppliers, and consulting companies over the life-cycle of a ship, the sharing and exchange of technological information are important factors so as to enhance productivity and competitiveness. Especially, the growth of the technology of information and telecommunications expedites the progress of globalization of shipbuilding and related industries. The engineering process maintained for the design and production of ships and marine structures must be restructured.

In this study, the construction of KSnet-based collaborative engineering system to cope with the change of engineering environments and to support distributed engineering environments is considered. Especially, this system supports not only for small and medium sized shipbuilding companies that have insufficient engineering capability, but also for the request of government.

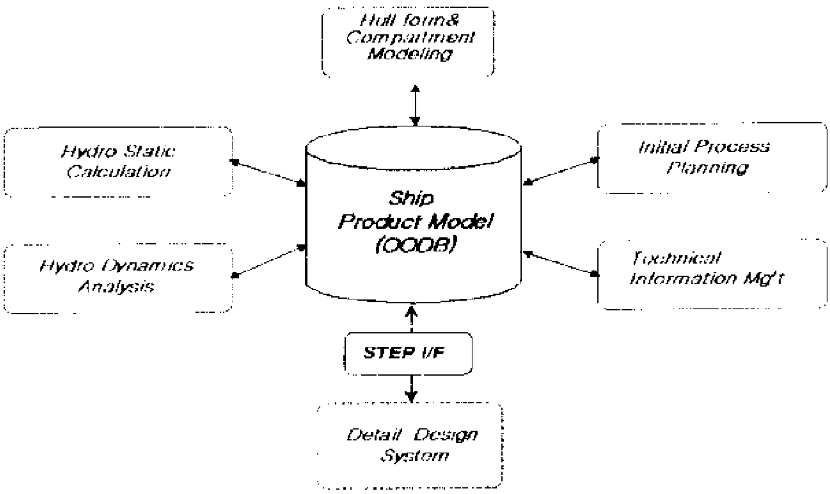

Figure 6. Configuration of Ship Initial Design and Planning System (The Frame System)

The Frame System

In Internet-based collaborative works for shipbuilding, close cooperation is the key factor among the distributed organizations, such as ship owners, classification society, marine equipment suppliers, model basin, and subcontractors around shipyard. In order to realize internet-based collaboration and to verify and integrate the related technologies and sub-systems, the frame system is presented for the planning stage of ship design.

As shown at Figure 1, the basic planning of ship design covers many activities before the contract of a new ship. In which the specifications to meet owners' requirements are determined, and modeling and performance analysis to support the design decisions are performed repeatedly. This stage is important in shipbuilding life-cycle, because in which not only the performance, price, and building period are determined, but also a lot of information for the activities of post-contract such as detail design and production are generated. Nevertheless, tools to support work activities and process for the planning stage of ship design is rare. Hence this frame system has been developed for the practical use of concurrent planning support system. Figure 6 shows the configuration of the basic planning support system. As shown at this figure, the system is composed of components, for examples, various CAE technologies (hydrostatics, hydrodynamics, etc.) to be used by the basic planning stage, ship price estimation system, process planning system, generation/maintenance system for technological documents, object-oriented product modeler, database for integration, and STEP interface system to interface with a detail design system.

To perform all sorts of functions under the distributed design environments, new design environments and tools are required. Figure 7 depicts the new environment for the ship basic planning. As shown at this figure, a new environment means the Internet-based collaborative work environment. To realize this Internet-based collaborative work environment for the ship basic planning stage, the following technologies are needed. SGML to exchange and share the technological documents, STEP to exchange and utilize the product model data, video conferencing to communicate with each other, and CORBA to share knowledge. The frame system is a tool to adopt these technologies from viewpoint of ship design and engineering concept.

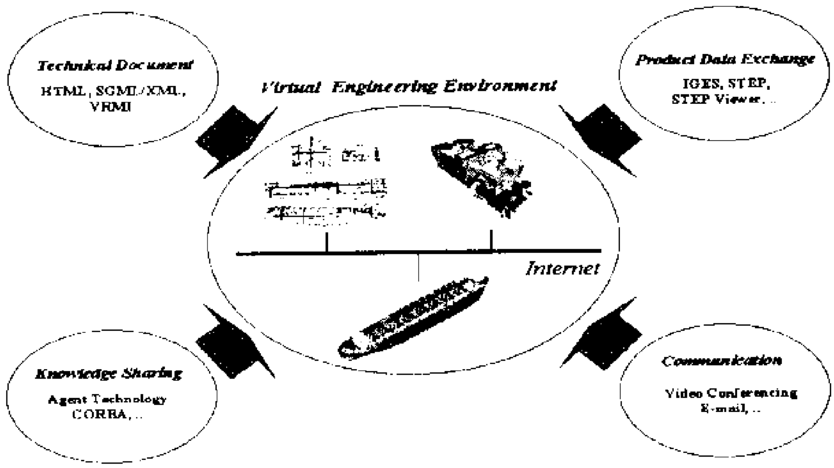

Figure 7. Technologies for Internet-based Collaborative Engineering

Scenario for KSnet-based CE

Figure 8 shows a scenario to be realized within the frame system. We focused on the activities of ship owner, classification society, model basin, and marine equipment maker centering around a shipbuilding company. The technological information which should be handled in this system are owner's requirements, basic calculation sheet, hullform model, machinery drawings, and specifications. In addition, this prototype system verifies not only the adaptability of all sorts of standard technologies, such as SGML, VRML, HTML, STEP for the construction of Internet-based collaborative work environment, but also the integration of ship modeler, STEP viewer, and document management system based on SGML.

Table 1 is a system environment to be implemented according to the scenario shown in Figure 8. As shown in the table, PCs for Windows NT, and workstations for UNIX are linked by the network. In addition, a word processor for the generation of technical documents, a ship basic calculation program (SIKOB), a CAD system (I/VDS) for 3-D modeling of hull and machinery are adopted. Netscape Communicator is used for the Internet browser.

Future Directions

In this project, the establishment of KSnet-based collaborative design concept, the frame system for the basic planning system, the definition of core technologies, the scenario of prototype, the construction of system environments, and the adaptability of standard technologies are carried out.

CORBA, agent technology, and STEP application technology will be adopted for the frame system. And also new concepts and emerging technologies are continuously accumulated based on the frame system. Apart from this project, the development of object-oriented ship modeler and model-based CAE, and simulation technology have been studied. By merging the results into this frame system, a practical remote collaborative design and engineering support system will be realized soon.

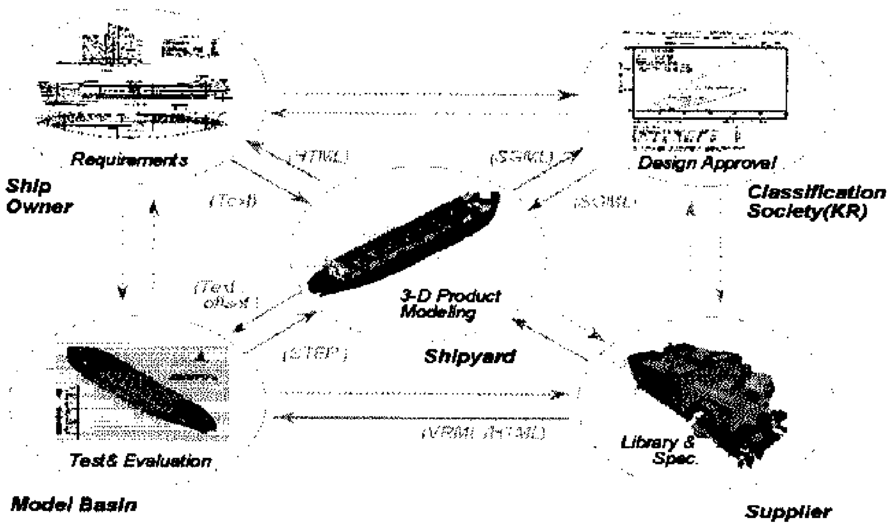

Figure 8. Scenario for KSnet-based Collaboration

Table 1. Components and Environment for the Frame System

	Shipyard	Model Basin	Ship Owner	Class. Society	Vendor
Application	Initial Ship Design& Planning - Hull Form& Compartment Modeling - Ship Hydrostatics - Process Planning	Ship Hydrodynamics - Power Estimation	(Ship Management System)	Design Approval - Damage/Stability	Product Data Management - Part Library - IETM
Data Base	- Std. Ship DB - Product Model DB - SGML DB	- Hull Form Model		- Rule/Regulations	- Std. Part Library - SGML DB
Utility	- STEP Tools - SGML Editor - Web Server - Web Browser	- STEP Tools - Web Browser	- Web Browser	- STEP Tools - Web Browser	- STEP Tools - SGML Editor - Web Server - Web Browser
Platform	- UltraSparc (Soleris 2.5.X)	- Pentium PC (Windows NT)	- Pentium PC (Windows NT)	- Pentium PC (Windows NT)	- Pentium PC (Windows NT)

Conclusions

The development of the information and communication technologies changes the shipbuilding industry in the 21st century into the knowledge-based industry. The Internet-based electric commerce and concurrent engineering environments will be settled down. Ship design and production process will be converted into the computer supported collaborative work system with distributed agents.

The aims of this project are to establish the infrastructure for shipbuilding industry based on information and communication technologies, and to establish the framework for collaboration. As a result of the study, the Internet-based network for Korean shipbuilders (KSnet) and the frame system of KSnet-based collaborative engineering have been designed and implemented. This project will be finished in the end of 2000, and not only the knowledge related to ships and ocean engineering can be shared, accumulated, and succeeded, but also the cooperation among the shipbuilding community will be promoted through the project. The emerging information technologies will be transferred to the shipbuilding industry.

Acknowledgement

The reported work is a part of KSRA project funded by Korean government and four major shipbuilding companies: Hyundai Heavy Industries Ltd., Daewoo Heavy Industry Ltd., Samsung Heavy Industry Ltd. and Hanjin Heavy Industry Ltd. The authors wish to thank the members of Information Technology Committee of KSA for the cooperation. They also wish to Mr. Bruce H. Bongiorni, the NSnet project manager of the University of Michigan Transportation Research Institute, for his information and guidance about the NSnet Project.

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THE DESIGN AND INTRODUCTION OF A COMPANY-WIDE INTRANET

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Abstract

Today the Hyper Text Markup Language (HTML) is a universal format for documentation and intranets. We describe the successful migration from paper-based documentation to an on-line, intuitive and interactive presentation of information. This new type of documentation is used as a design and training aid within the technical departments of Harland & Wolff (H&W). HTML and a browser are used for the presentation of documentation on a company wide intranet. There are similarities between our intranet and the Internet as we adopted some of the principles of the WWW (World Wide Web). At present, the user of the intranet has company wide on-line access to documentation that contains shipbuilding and off-shore discipline specific topics. This new type of tool gives the users access to information about best practice and makes extensive use of examples. The design information tool can be used by the draftsmen concurrently with the actual design they are working on.

Harland & Wolff transformed the idea of an intranet into a workable tool for the designer. The designer can use this tool on a day-to-day basis and contribute to its contents and appearance. In the process of establishing the intranet, we used conversion tools and a toolkit to create a suitable environment for our ship-building and offshore company. There are distinct differences between setting up an intranet and publishing web pages. In Harland & Wolff's case, both were developed simultaneously.

Introduction

This paper will give background information about the company and describe the nature of the business. We will define the terms used in the context of the paper. The aims of the project and benefits to the business will be described. The paper will present details on the implementation of the project and lay out the individual steps we followed to realise the intranet. We will conclude, by presenting the results.

Company Background

Since 1861, over 1700 ships and marine structures have been built by Harland & Wolff at its Queen's Island site. From offshore structures, huge oil tankers, naval ships and luxurious cruise liners, the Harland and Wolff name has long been associated with innovation and quality. Many vessels were at the leading edge of technology at their time of construction. Today, Harland and Wolff is established as a major contractor to the offshore oil and gas industry [HW].

Set Up of Technical Departments

In the technical departments approximately 200 designers work on CAD stations. The last drawing board was made obsolete about three years ago. This means a full commitment to an electronic representation of the design information. These designers are working concurrently in disciplines like Hull, Outfit, Machinery, Electrical, HVAC (Heating, Ventilation and Air-Conditioning) and Piping and Instrumentation Diagrams (P&ID's). They all contribute and maintain a wholly CAD-supported full product model. Designers share all modelling information as they work on the same databases for hull panels, equipment, HVAC and piping. Only 2D drawings as a matter of preference are kept in directory structure according to discipline.

Within the past five years, there has been a gradual transition from core draftsmen to contracted designers. This required a shift of knowledge and tasks for the designer. More than at any time in the past training, sharing of company standards and easy access to help and documentation on the system is vital.

Definitions and Discussion of Terms

Intranet Definition

An intranet is the implementation of Internet technology within a business. Technically, an intranet is a client/server computer system. It differs from typical client/server systems because it uses a web server program on the server computer and a browser program on each user (client) computer. Intranets allow user to search for, retrieve and display documents, to use electronic mail (e-mail), and to collaborate on projects [INTRA].

A Company-wide Intranet

A company-wide intranet is the ultimate goal of the project. At present we have restricted access to the intranet to those in the technical departments. This is because most of the engineering knowledge of the company is held within the disciplines of the above mentioned technical departments. Another reason is that, publishing company internal information on finance, personnel or other private matters would have compromised the security of the company.

Definition and Advantages of HTML Against Paper Based Documents

The first Hypertext application, which was developed at CERN (European Laboratory for Particle Physics) [CERN], initially targeted an intranet application. It was aimed at sharing documents and scientific results in a heterogeneous and distributed environment.

Publishing information for global distribution requires a universally understood language that all computers can interpret. The publishing language used by the World Wide Web is HTML.

HTML gives authors the means to:

- Publish documents on a computer that includes headings, text, tables, lists, photos, etc.
- Retrieve online information via hypertext links at the click of a button.
- Design forms for conducting transactions with remote services, and searching for information, making reservations, ordering products, etc.
- Include spreadsheets, video clips, sound clips, and even other applications in their documents.

HTML was originally developed by Tim Berners-Lee while at CERN. It was popularised by the Mosaic browser developed at NCSA (National Center for Supercomputing Applications). During the course of the 1990s, it has blossomed with the explosive growth of the Web and has been extended in a number of ways. The Web depends on Web page authors and vendors sharing the same conventions for HTML. This has motivated joint work on specifications for HTML [HTM].

Paper based documentation in contrast, has got the follwing disadvantages:

- Paper copies are not consistent and therefore hard to update and revise.
- Paper copies are spread out and are held by different departments.
- Illustrations might have different sources. The original source could be hand drawings, photocopies, drawings from design system etc...
- Cannot be browsed
- No full text search possible

Most of these features are available using HTML and a browser.

Aims

The main aim of the project was the successful substitution of existing paper-based information within a simple, easy to access, flexible and comprehensive alternative.

First, we had to identify appropriate technology and hardware for the best use of an intranet. Next, we agreed on the usage of a well known and widely used standard to gain the advantages of a platform-independent protocol.

The chosen standard of HTML accommodates the company's two main operating systems of OpenVMS and Windows NT.

We wanted to explore the possibilities and limitations of a company-wide intranet. Finally, we were interested in finding out to what extend and by which disciplines an intranet could be used.

Implementation

The implementation was carried out in three major steps. These steps were first to migrate from paper based documents to digital format. Then the second step was to convert the documents to HTML. The third step was testing and publishing.

Migrating Paper-based Documents to Digital Format

The first step was to migrate the paper-based copy to a consistent electronic format. To accomplish this, the documents were compiled and the existing paper-based documentation was converted into digital files. Existing illustrations and figures were scanned into a word-processing application.

Converting to HTML

This was done by either using two utilities: RTFtoHTM conversion utility [RTF] or Internet Assistant which is an add-on for Microsoft Word [IAS]. The hypertext references were created according to the HTML language specification with a standard text editor on the particular operating system. Figure 1 shows the appearance of the hypertext in a browser. Figure 2 shows the underlying text according to the HTML language specification. The page shown is a top level overview of the H&W intranet. Below that, the documents are organised in a directory structure according to discipline. The operating system used is Windows NT or OpenVMS, depending on where the tests are carried out and the hypertext is published. Illustrations within the documents are automatically converted into GIF (CompuServe Graphical Image Format) files and references to these files are generated by the conversion software.

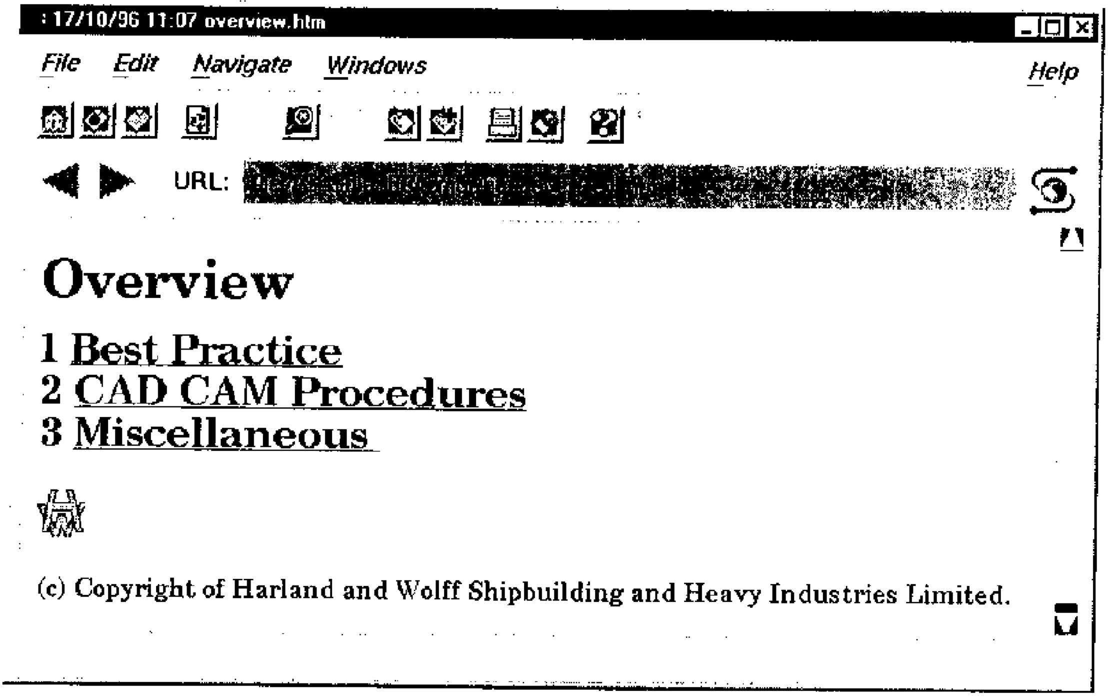

Figure 1: Appearance of Hypertext in a Browser

```
<HTML>
<HEAD>
<META HTTP-EQUIV="Content-Type" CONTENT="text/html; charset=ISO-8859-1">
<TITLE>17/10/96 11:07 overview.htm</TITLE>
<META NAME="GENERATOR" CONTENT="Internet Assistant for Microsoft Word 2.04z">
</HEAD>
<BODY>
<H1><A NAME="RTFToC1">Overview </A></H1>
<H2><A NAME="RTFToC7">1 </A><A href="best_pra/content_best_practice.htm">Best
Practice</A>
<BR>
2 <A href="procedur/ccindex.htm">CAD CAM Procedures</A> <BR>
<A NAME="RTFToC8">3 </A><A href="misc/acronyms.htm">Miscellaneous </A>
<BR>
</H2>
<P>
<IMG SRC="hw_logo.GIF">
<P>
(c) Copyright of Harland and Wolff Shipbuilding and Heavy Industries
Limited.
</BODY>
</HTML>
```

Document Name

Heading

Hypertext Link to Page

Embedded Figure

Figure 2: Underlying HTML Code for Page in Previous Figure

Testing and Publishing

During testing, a browser that was compatible with the operating system was used. That was Netscape [NETS] for Windows NT side and Spyglass Mosaic [MOS] for OpenVMS.

A first round of testing was done locally on a PC with Netscape running under Ms Windows NT. The HTML files and the associated directory structure were then copied over to the Test Alpha server. After successful testing on OpenVMS, the HTML files were then, placed on the live OpenVMS cluster. The current situation is that the main documents of every discipline are stored as HTML files on the Test Alpha server and mirrored on the live cluster. At the moment we are running demos that illustrate the appearance and help us to agree on a common outline. To assure the consistent appearance of all documents, we need a style guide that must be followed during the development of the intranet and while writing the documents. After streamlining the documents and loading a new version of DEC Windows, the same browser will be available on the main Alpha cluster. At that stage, the documents will be available for all designers working at a CAD station.

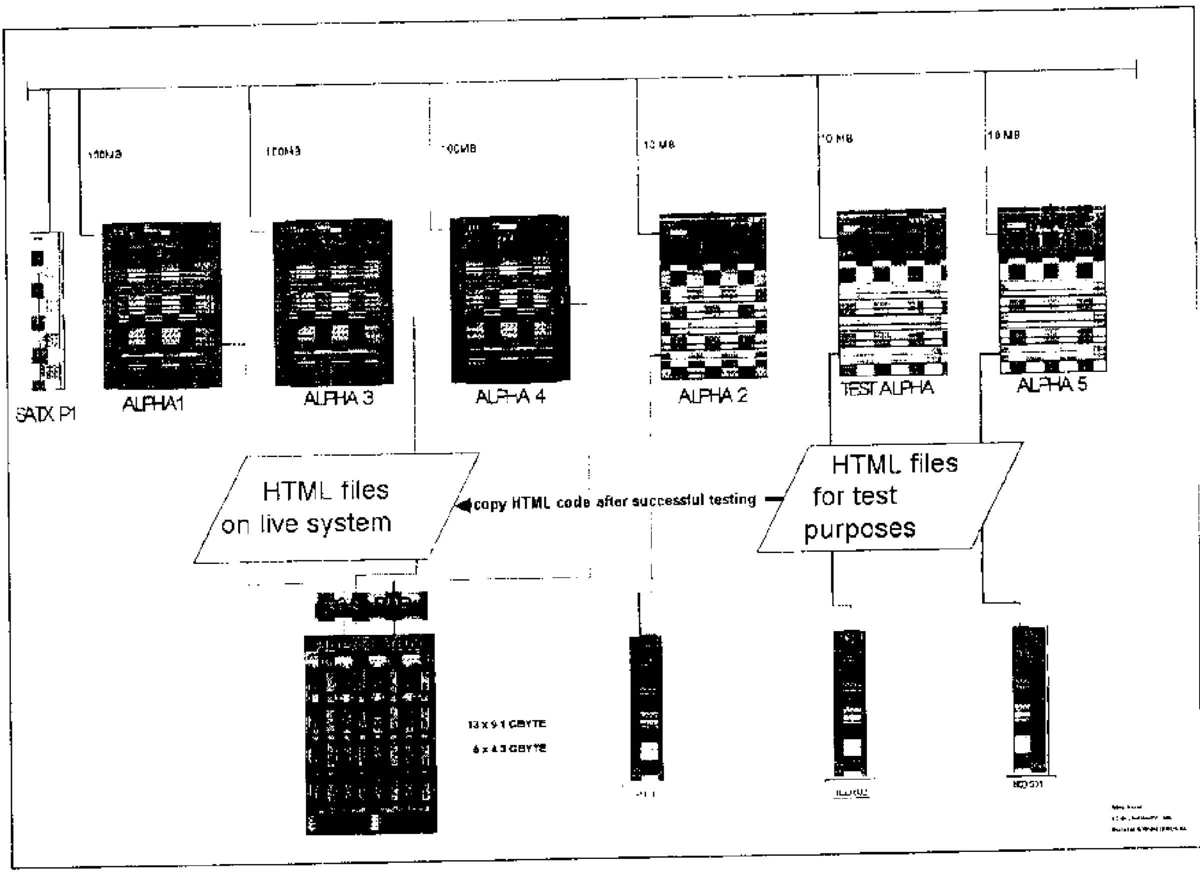

Figure 3: System Environment

Usage

Usage of the Browser

The usage of the browser is very simple and straightforward, so there is no need for training on how to browse the documentation. However, some time should be spent on showing users how to apply the full text search. This will allow the user quick access to very specific topics.

The presentation of the documentation in free text flow (no end of line marker) allows the user to have documentation displayed in parallel with a CAD session on the screen. Document templates and e-mail templates can be spawned from the browser. We use the spawn function to assist new CAD engineers in following a step-by-step procedure to fill in error report forms to then assign these forms to the helpdesk of our CAD supplier by e-mail.

Indexing

The implementation of an index in combination with a comprehensive full text search on all indexed documents will result in fast and successful searches on any topic or keyword.

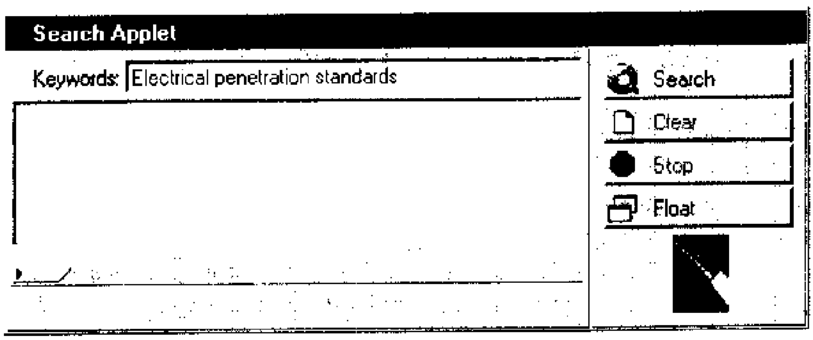

Figure 4: Search Applet

Results

The project facilitated a team-worked solution among the designers and close co-operation with engineers. The technical staff was given a versatile tool to document their work and procedures. We developed a structure and test case for the successful implementation of a company wide intranet. All processed documents are now available to all relevant personnel with a quick and easy-to-use full text search across both operating systems.

Acknowledgements

We would like to thank all H&W staff and employees who contributed to the creation and maintenance of the project.

References

[CERN] http://wwwas.cern.ch

[HTM] http://www.w3.org/MarkUp

[HW] http://www.harland-wolff.com/overview.html

[IAS] Microsoft Internet Assistant; http://www.awa.com/nct/software/webtools.html

[INTRA] http://www.sedonamg.com/intranets.asp

[MOS] Spyglass Enhanced Mosaic; Guide to Open VMS Version 7.0 ; Digital Equipment Corporation , Maynard, Massachusetts

[NETS] http://www.netscape.com

[RTF] http://www.sunpack.com/RTF/rtftohtml_overview.html

WEB ENABLED MANAGEMENT

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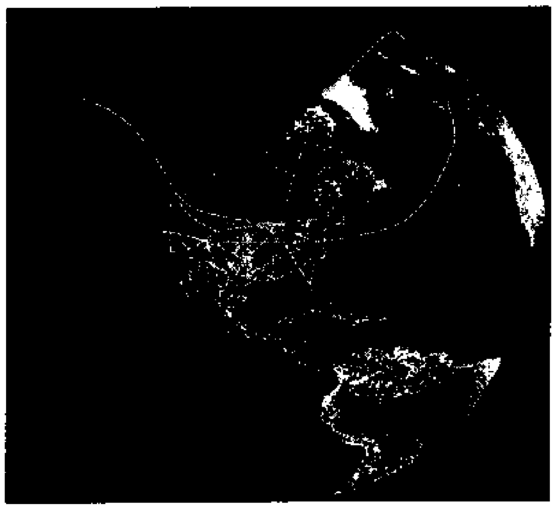
Abstract

The authors have been involved in the application of Virtual Working Environments to ship design, construction, and acquisition management. The following summarizes the authors' experiences, the benefits derived from the approaches taken, and future applications derived from those experiences. The emphasis is on practical near-term application using current technology in contrast with larger scale architectures using future technology. Under a 27 month DARPA Maritech Project, Nichols Advanced Marine, Intergraph, Avondale Shipyard, Raytheon, and Orincon systematically reengineered the early-stage ship design process. The resulting information technology solution was developed to: accelerate the design process; enable a distributed enterprise; improve customer interaction; support concept development using a product model; utilize legacy data; and permit smooth transition to later stages of design and construction without re-entry of data. The approach was applied during a Pilot Project and has been tailored for application to other programs. Experiences are discussed to highlight common infrastructure and processes.



Introduction

Web Enabled Management for shipbuilding is the application of web technologies to provide information to a group of participants, and manage their information access, in order to expedite and document the ship design process. It is an overlay above engineering calculations, modeling, and design software that takes the form of extra- and intranets and newsgroups in order to communicate critical information in a controlled yet readily accessible format. Web enabled management is vital to the success of virtual shipbuilding enterprises and other distributed enterprise efforts. It is particularly important to shipbuilding enterprises dealing with unique or special purpose ships. Integrated enterprise approaches do not require expensive software solutions. They require a commitment to new processes and the application of common communications and data management tools. Web enabled management incorporates and strengthens the advantages of product modeling and information management tools. Key points to be addressed include:

- Virtual Enterprise approaches are required in shipbuilding;
- Information technology offers continuously improving capability for ship design;
- Web enabled management is key to effectively using information technology;
- Special purpose ships are the most attractive candidates for Web Enabled Virtual Enterprises;
- Commercial-off-the-shelf software is sufficient to achieve these benefits; and
- Business processes must evolve to suit these approaches.

The Global Economy, the Business Case for Working Together

Ship design and construction, like all complex processes, is undergoing a period of rapid and accelerating change, caused by world events and new technology. The globalization of the economy, the presence of the Internet, new product modeling and management software, and advances in information technology, are factors contributing to this new business environment. Overcapacity forces shipyards into tighter competition. Corporations are forced to concentrate on their main business and are increasingly reliant on subcontractors or partners. Alliances previously unheard of are becoming common and range from mergers of entire companies, to cooperative joint ventures focused on a specific product. In this business environment it is more appropriate to think in terms of an enterprise, rather than a single shipyard. The enterprise may include a variety of design, fabrication, assembly, and supplier companies that together can offer the best product. The motivation for working together is clear; the collective talents of an enterprise often can produce a better product than a single business. For the business case to be clear, we must enable the enterprise to work together without suffering inefficiencies or delay. The distributed talent must work together as a Virtual Enterprise.

The Need for Web Enabled Management

Exchange of information is central to the function of any business. Barriers to communication exist between corporations and even internally within single companies. Communications technologies and protocols such as STEP continue to advance and provide for improved data exchange, making it easier to share information across corporate boundaries. The small supplier that depends on AutoCAD can exchange data with the shipyard that uses high-end product modeling software such as Intergraph's ISDP or GSCAD system. Object oriented approaches allow direct incorporation of documentation, calculations, and information into product models. Hardware improvements increase processing speed, reliability, and the amount of data that can be managed. Effective use of this infrastructure requires business practices, policies, and procedures to coordinate the Virtual Enterprise. This is true for any industry in which distributed teams develop complicated products; the following quote highlights one example: *"To reduce the cost of collaboration with contractors, Robert Stephens, Lockheed's manager of joint strike fighter (JSF) information resource management, turned to an extranet....Stephens says when the contract was out for bid back in 1996, the DoD saw the plan for Internet-based communications between team members as a differentiating factor that helped Lockheed win a berth in the next round of the JSF contract competition.*[1]"

Program Management of a Virtual Enterprise has all of the challenges of traditional, face-to-face program management of a collocated team, compounded by the need to overcome the separation of participants. Professor Tom Allen of MIT studied the efficiency of collaboration as distance increases, finding that beyond a radius of fifty feet, the people might as well be in another country, because people will not walk that distance to talk face-to-face.[2] Shipbuilding companies tend to be large and distributed, and the trend seems to be continuing. For example, as this is written, Avondale, Newport News, and General Dynamics are considering mergers to form a shipbuilding conglomerate

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[1] CIO Feb 1, 1999

[2] Virtual Teams, Jessica Lipnack and Jeffrey Stamps, John Wiley & Sons, 1997.

in the United States. Nichols Research Corporation boasts of 27 offices in 15 states.[3] In that counting, "Crystal City, VA" is grouped as 1 office, yet it actually occupies 7 floors of 3 buildings, as well as many more 1 and 2 person offices. So, even when looking internally at just one company, collaboration is complicated by separation.

Consider the case of a shipbuilder discussing the potential design and construction of a new and unique ship with a ship operator. The shipbuilder will apply its expertise to design a ship that meets the customer's requirements, using any of several powerful ship design software packages to perform the design effort. During the first days of the concept design effort, details are not addressed. Many alternatives are quickly evaluated and compared. Performance predictions are made to validate the concepts. Cost estimates are made and production planning is conducted. The concept development process is conducted in weeks rather than months. Possibly, the entire effort can be conducted in-house. More likely, the shipbuilder will utilize other companies to either supplement their workforce or to provide specialty expertise. Often the team will be forced to collocate to a common site. The supporting organizations may not have the identical software or capability. However, they require access to the same information. A range of data transfer alternatives exists, from hard copy material to direct digital transfer of information. Contrast this with an environment in which: partners contribute from their home offices; team members work in parallel, accessing data from a common site; data is immediately available to anyone that needs access to that data; new team members are added quickly and efficiently; and design decisions are documented automatically as the design progresses. Web enabled management offers these advantages through the application of relatively inexpensive software.

Web enabled management unites business processes with the infrastructure of information technology to provide leadership, efficient execution, and accountability within a Virtual Enterprise.

Leadership, Execution, & Accountability

Within a Virtual Enterprise focused on shipbuilding, there is a core group that has the greatest amount of risk and potential reward. It is this Core Virtual Shipbuilding Enterprise (CVSE) that provides the leadership to unite an effective team. A Web Enabled approach minimizes travel, minimizes communication barriers, and makes it easy for the CVSE to add new team members. Execution is improved through web enabled management because decisions are made more rapidly and information related to design decisions is immediately available to the entire enterprise. Requirements are clearly defined. Design products and internal communication are linked directly to the requirements. Design efforts are carried out concurrently with results visible to the team for comment and further action. Product modeling approaches can be an integral component of Web enabled management, minimizing rework and re-entry of data. Legacy data is used more effectively and information generated will carry forward with greater efficiency. Consistent visual representations of the final product are provided to the enterprise, including those participants not equipped or trained to use the product modeling capability. While formal design reviews should still be encouraged, web enabled management provides for continuous review of the entire product. Interaction with the customer is enhanced. Customer access to design information is provided on a continuous basis. Comments are provided to the Enterprise at the convenience of the customer. The connection between design results and requirements will be much clearer; web links tie results immediately to the associated requirement. Productivity, or lack thereof, is immediately visible. Accountability is enhanced because the assignments of work to, and responsibility held by, each participant is well documented and accessible to all team members. With web enabled management, the right team is brought together to rapidly perform engineering in support of a ship design project.

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[3] Nichols Research Corporation '97 annual report.

Specialty ships and Web enabled management

Enterprises producing special purpose ships are in the best position to benefit from the application of integrated enterprise approaches to make their products more competitive and to make their enterprises better able to:

- rapidly offer new products,
- bid and negotiate contracts with confidence, and then
- conduct detail design, construct, and deliver the desired ship.

Design effort is minimal for repeat designs and engineering effort is focused on production efficiencies. Construction costs are well understood and pricing can be aggressive. Even in this segment of the shipbuilding industry, alliances and joint ventures are pursued. When an existing design is unavailable for a particular owner's requirements, the scope of the design effort is obviously increased. The shipbuilder marketing a specialty ship must conduct concept development, drawing on experience, knowledge of engineering and production processes, and supplier information, in order to define the product, plan the effort, and establish a reasonable price. Rapid, confident response to the customer is essential. The special purpose aspects of the design minimize the extent to which existing designs can be used, although re-use of components of existing designs is attractive. The enterprise that can most effectively respond may include many participants. Web enabled management is particularly valuable for specialty ships because it facilitates rapid design development concurrent with rapid team forming so that, in the early weeks of conceptualization and customer interaction, the best possible enterprise is formed as the design is developed.

Web Enabled Management Components

It is the authors' experience that existing commercial software products can provide the necessary infrastructure for effective web enabled management. While shipbuilding specific software is essential for many functions within the ship design process, Web enabled management does not demand custom software. Advantage can be obtained by using products that serve the broad information technology market. International software suppliers invest far more in product development, maintenance, and support than an individual shipbuilding enterprise could ever invest. These products can effectively interact with specialty shipbuilding software and can be selected to adapt to specific enterprise preferences. The core elements include:

- Product modeling software, capable of digitally modeling the entire ship;
- Internet based communications infrastructure, providing sufficient bandwidth and secure access for distributed participants;
- A browser based approach for providing access to and managing design information;
- Newsgroups for logically tracking communications and decisions made by the design team.

A modest technical solution or a robust technical solution can support web enabled management. In its simplest form, web enabled management requires only a web server, web pages, an FTP site, discussion groups, and business rules that standardize the use of the technology. At its most robust, the technology is an integrated web-based front end to an Integrated Data Environment. Table 1 lists the technology that could be involved, depending on the level of sophistication required by the team.

Table 1: Web Enabled Management Functionality

Server Functionality	Framework Functionality	Applications Functionality
Web-Page Viewing • HTML • GIF, JPEG • VRML • movies (e.g. AVIs) • CGI Scripts • JAVA applications • + next generation File Transfer Newsgroups Security • Certificates • Secure Socket Layer • Encryption Backups User Logs	Document Management • Config Control • Multi-Level User Access • Document History Documents Mapped to Applications Document Catalogs Document Libraries Document Vaults Workflow	• Requirements Management • Action Items • Calendar • Schedule • Case History • Design • Visualization • Analysis Tools • Redlining Sessions • Collaborative Model Review

As shown in Table 1, the functionality falls into three categories. The first is the web server technology. These functions are common to most intranets and extranets.[4] The web server technology acts as an intermediary between the information and the clients. The second set of functions pertains to document management, including configuration management and workflow. Document refers to any collection of information, including memos, spreadsheets, drawings, pictures, and databases. The third set of functionality is specific to the particular problem. In the case of ship design, the CAE tools and the analysis tools come to mind. One could well imagine a similar set of tools being used to discuss automobile design, software design or surgery preparation, but in those cases the tools would be specific to those particular problems.

MAAST Project

A DARPA MARITECH[5] project called MAAST (Maritech Agile Shipbuilding Toolkit) provided a recent opportunity to apply web enabled management to the concept design of a roll-on/roll-off ship concept. The MAAST project started in July 1996, ended September 1998, and focused on the early team-building stages of ship production. Hughes (now Raytheon), Orincon, Avondale, Intergraph, and Advanced Marine Enterprises, (now a business unit of Nichols Research, doing business as Nichols Advanced Marine) teamed together to perform systems and business process reengineering of early stage ship design. Early on, Avondale set the goal for the team; accelerate early stage ship design by 100%. This was taken to mean achieving a defined level of concept definition starting from "a blank sheet of paper" in six weeks rather than twelve. By setting the pace of early

Intranets are web sites that only one organization can access. Extranets are web sites that a controlled group of rganizations can access. Though the network could be a private and therefore more secure network, generally the nformation is passed over the Internet, in encrypted form.

For more information, see www.nsnet.com, Maritech stage ship design, the team would gain a competitive advantage. This advantage may manifest itself as an earlier delivery of a bid package to the customer. Though the 50% cut in calendar time does not imply a savings in resources and cost, an increase in the pace is often the first step in making a process more efficient.[6] There is less time to waste, and therefore only the value-added processes are emphasized.

After the goal setting and team formation process, the group went through an extensive system engineering process. At first the process was narrowly focused on early stage ship design. As time went by, the team began to realize that the focus solely on the mechanics of ship design missed the point. The team broadened its focus to include the virtual enterprise formation process as well. Experts from the Iacocca Institute at Lehigh University counseled the team on agile team forming. Agility means responding competitively to a customer's needs in an environment of continual and unpredictable change. The final IDEF0 Diagrams were titled "Execute a Virtual Agile Shipbuilding Enterprise." The new process description started with the creation of a web of relationships that an organization could draw upon when a new opportunity presented itself. Next, it focused on the process of creating a virtual enterprise that will respond to the opportunity. Then, the virtual enterprise produces a ship. Finally, the enterprise distributes risk and reward, and disbands or goes into a dormant state.

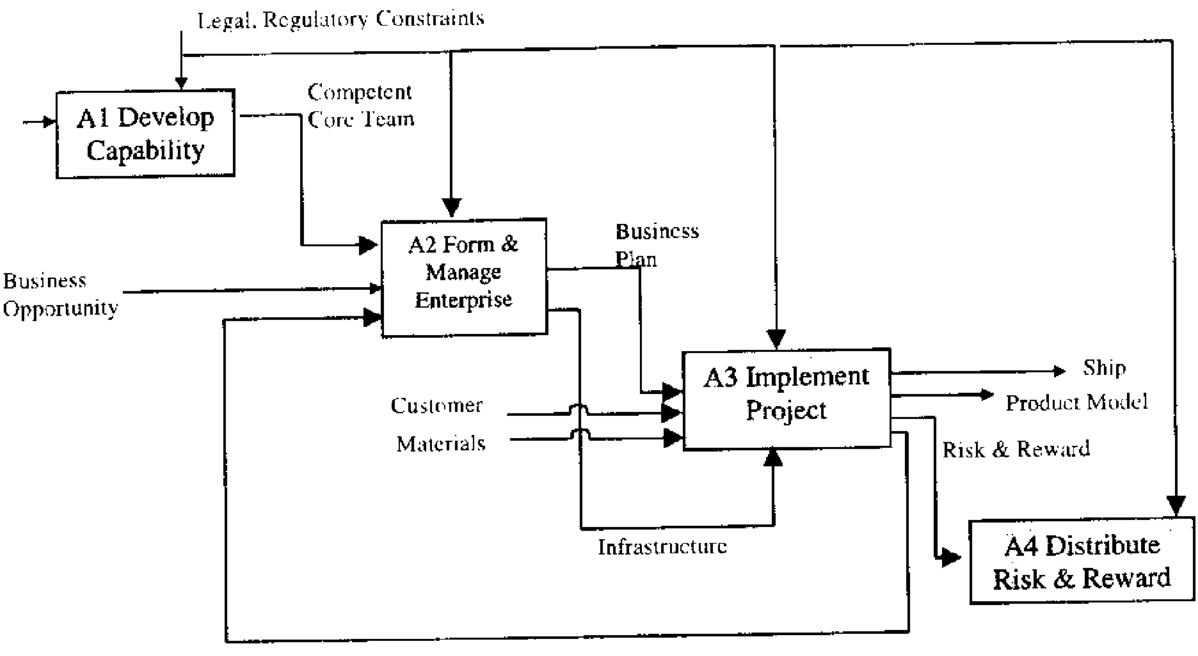

Figure 1: Top Level Virtual Shipbuilding Enterprise Process

The MAAST Pilot Project

To test the MAAST infrastructure and process, a six-week long, unscripted Pilot Project was conducted. There were only a few ground rules. The Pilot focused on a Roll-On / Roll-Off ship, since this ship type represented a specialty ship requiring considerable concept development to meet owner requirements. To make the design as commercially meaningful as possible, a commercial operator

[6] In Search of Excellence? Also in Cooperate to Compete, Chapter 5, Adding Value by Subtracting Time, Preiss, Goldman, and Nagel, Van Nostrand Reinhold, 1996.

was invited to participate, providing design requirements and reviewing the results. Norman Gauslow, General Manager, Marine Operations, of Crowley American Transport, Inc., accepted the role of customer during our Pilot Project. Before the Pilot, the MAAST core team approached MacGregor, York Marine Systems, and Harris Fire Protection Company. These three suppliers were brought onboard before the Pilot started, reflecting a commitment on the part of the team to design ships with equipment from these companies. Other suppliers, such as Wärtsilä, were not integrated beforehand, so that Crowley had some choice and influence of the design. Crowley expressed an interest in Intering Stability systems. These gave the team opportunities to integrate important suppliers during the six weeks. The participants in the project are shown in Figure 2, clearly an example of a distributed enterprise.

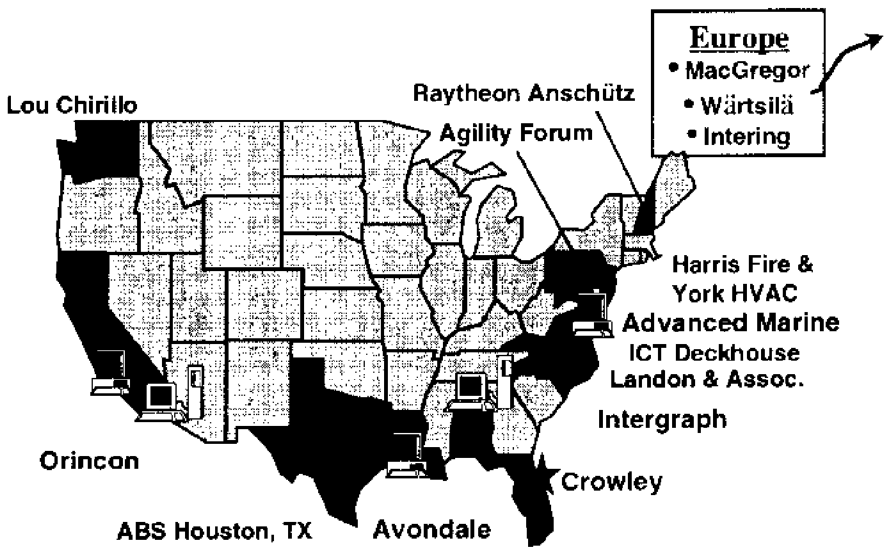

Figure 2: MAAST Pilot Virtual Shipbuilding Enterprise

Membership

Membership is the most powerful control that leadership has over a virtual enterprise. Choosing the right partner, supplier or customer will improve the performance of the team drastically. The new member must share the appropriate amount of risk, responsibility and reward. At the Iacocca Institute of Lehigh University, the three dimensions of performance are supplier reward, customer benefit, and technology. Membership is the appropriate time to address these three dimensions. Mission-critical members command high reward and are integrated in a technically advanced way. Non-critical members will be less integrated into the virtual enterprise, on any of the three axes. The central insight of Lehigh is that these three axes have to be in balance, or the situation is unstable.[7]

The mirror image of the new member process is the member exit process. Members who are not world-class at any of the tasks no longer add any key value to the virtual enterprise. They must be asked to not participate in this program. Strategically, these members might still be very important to other programs that the virtual enterprise is pursuing. Therefore, these members will be inactive or dormant for this particular program, but remain connected for other programs. Enterprise formation must be conducted with an eye on the conclusion.

[7] Cooperate to Compete, Preiss, Goldman, and Nagel, Van Nostrand Reinhold 1996.

Members of a Virtual Enterprise will demand appropriate security protocols to protect business sensitive data. Typically, security is more of a procedural problem than a technical one. It is becoming easier to provide a reasonable level of security, as evidenced by the increasing number of people willing to risk shopping online. For projects like MAAST, more thought and effort must go into the security plan for access to information. It is hard to divide the information into separate classes, where all the right people have access and all the other team members do not.

MAAST applied during the Pilot

The heart of the MAAST infrastructure is the Extranet, the Product Model Database, and the CAE tools, shown in Figure 3. The three-tiered approach to the infrastructure reflects the costs associated with adding knowledge. It was cheapest and quickest to have an engineer propose a solution on the Extranet. It was more expensive to create the list of parts that this solution entails. Finally, it was most expensive to model the parts in 3D CAD. Once the information is modeled in 3D CAD, it is the most accurate, and the CAE system was used to update the Product Model database. Graphics from the CAE environment and Bill of Materials created from the Product Model database were posted back to the website for dissemination to team members who could not access the CAE environment.

The appropriate use of the right technology will greatly improve the performance of the team. A range of solutions exists, from e-mail through Integrated Data Environments, each with a characteristic cost and benefit. The cost-benefit equations must be optimized to maximize value. The MAAST Extranet made it very easy to add new members to the team when the direction of the design shifted. This feature is particularly attractive during the initial weeks of concept design.

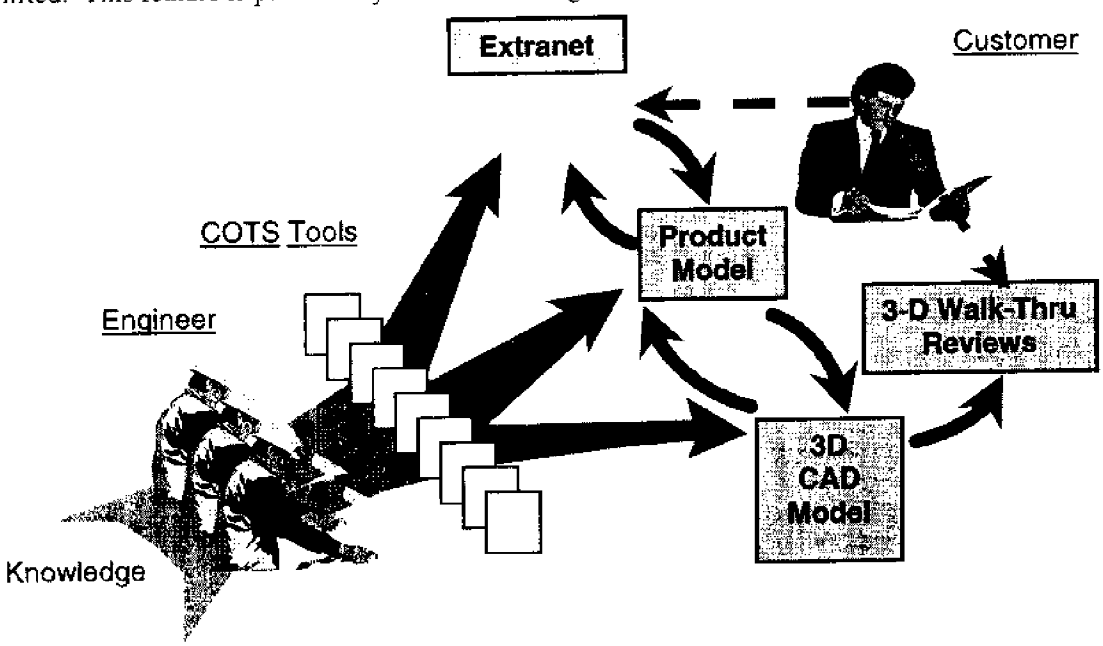

Figure 3: MAAST Infrastructure

The MAAST extranet was a set of web pages and discussion groups. The summary web page is shown in Figure 4, and is typical of the pages on the Extranet.[8] There is a table of documents, their respective authors and published dates. The documents were often stored in two formats, one that was web-ready (e.g. html) and another in the native format of the appropriate application (e.g.: WORD, EXCEL, or other programs accepted by the enterprise.) The web-ready format was often a summary of the more detailed document stored in a native format. The last column was a crude configuration control tool. Documents were applicable to a current iteration, denoted by the "Ih" reference, and were at a certain level of certainty or completeness, denoted by the "III" Maturity Assessment.

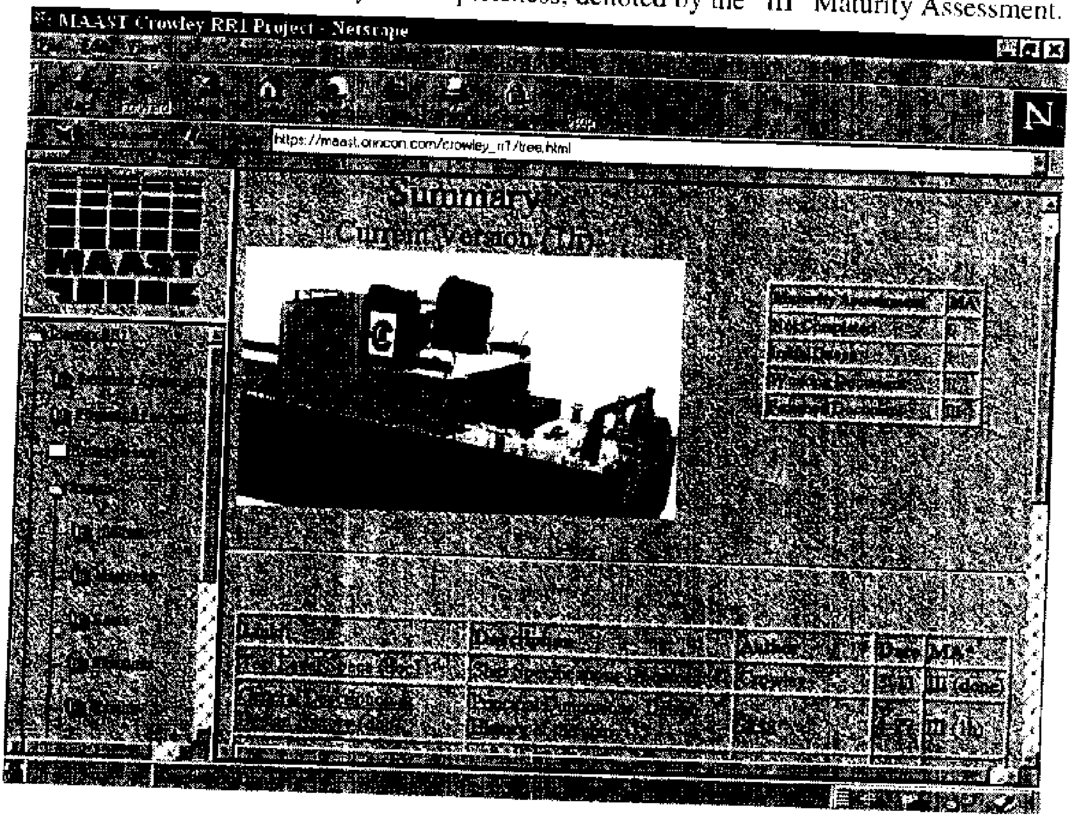

Figure 4: Summary Page

Configuration Control

Coordination and configuration control become increasingly important as the number of participants and their distribution increases. In addition to utilizing any version controls or workflow features inherent in the chosen modeling software, the distributed enterprise should apply web enabled management techniques to insure that all participants understand what information they are using and what they should be doing. The users without direct access to the high-end modeling capabilities still need to understand what configuration they are looking at. In the early stages of conceptualization many parallel paths may be addressed in parallel with significant changes occurring hourly.

Content is available online during the conference, at maast.nichols.com. Login name and password are "demo" and "demo" respectively.

Parallel Effort

In a parallel design process with online communication, it becomes the responsibility of the team members to keep up with the pace of the design. Each team member must understand the current state of the design and what issues are raised by changes. If the design is not satisfactory in an area, the area expert is expected to speak up. Silence implies agreement. Engineers hate to be proven wrong, particularly in a visible forum like the discussion groups. Often, people will not speak up with their tentative findings because they are not completely certain of the results. Management must work to encourage people to put their initial conclusions and concerns on the table, even if mistakes are made.[9] Discussion groups provide a mechanism for promoting and documenting this interchange.

Discussion Groups

Discussion groups, as shown in Figure 5, are an organized form of e-mail. Instead of sending the e-mail from one person to another, or from one person to a list of people, the e-mail is sent to a central persistent public location. The physical parallel is an office bulletin board. Everyone who has access rights can visit the discussion group and see the message, taking whatever action they deem necessary in response to the e-mail. Because the audience is determined by the system rights, and not by the author of the message, it is more likely that the right people will see the information. For example, the author of an e-mail might ask the customer a technical question. If this is done through

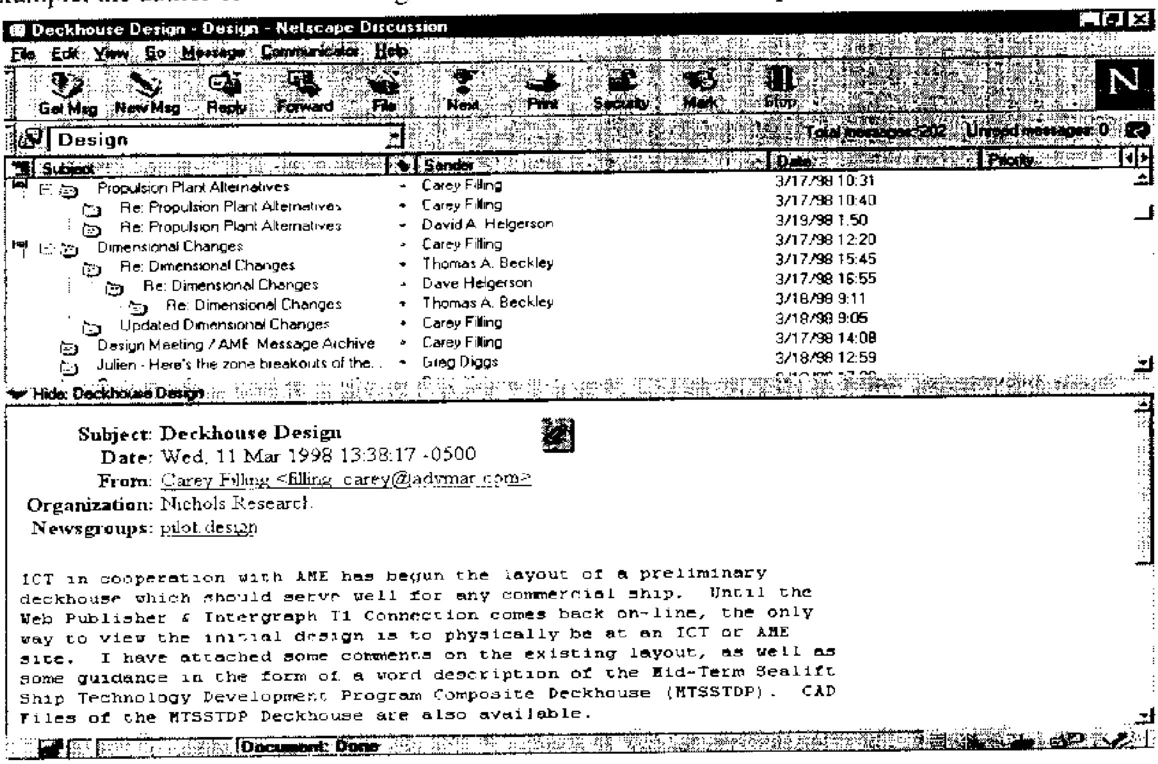

Figure 5: Discussion Groups

[9] "In this company, you'll be fired for not making mistakes." Steve Ross, late CEO of Time Warner.

standard e-mail, only the author and the customer will participate in the conversation. If this is done through a discussion group, then a third party who had the same question can benefit from the customer's response. Discussion groups present the information in many ways. The messages can be threaded together, so that the conversation threads are consistently grouped, as is shown in Figure 5. The messages can also be sorted by read and unread, sorted by date or author. Discussion groups naturally create a thorough design history. Often, a casual scan of the subject headings gives a good description of the project. In traditional e-mail, the same information may exist, but it will be dispersed over everyone's inboxes, and may be deleted by the participants. Because deliverables were on the web server, users could quickly and easily reference the calculations that had driven the new changes. This approach of referencing documents into other documents was used throughout the project. Figure 6 shows the General Description and Design History document. The use of discussion groups is simple, but has a remarkable impact on enterprise effectiveness.

Enterprise Member Credentials

When working in a web enabled management environment, some coworkers may be unfamiliar with one-another. Features may be incorporated to create a "virtual reputation." In person, physical appearance and credentials help to establish the reputation of a person. In addition, colleagues can vouch for a person's reputation, credentials and expertise. When a recommendation or comment is made online by an unfamiliar enterprise participant, other engineers benefit from information on the team-mate's background. For the virtual office to really be effective, it is important that each new member post a biography of past accomplishments and credentials. This should be posted along with the information regarding assigned responsibilities.

Modeling and Reviewing Models

The MAAST extranet was very simple. In the future, it would be appropriate to use a more rigorous web server architecture, perhaps supported by Microsoft Active Server Pages and Microsoft Back-Office. With more elegant web-solutions, the engineers can be directly responsible for entering deliverables into the document management system, whereas during MAAST only one person was able to author content onto the website. This became a choke point in the system. There is now a range of solutions to the extranet problem, some custom and some that can be purchased as commercial off the shelf software.[10]

The Product Model database was an Intergraph product called Product Model Environment. PME, built on top of an Oracle database, and developed for the US NAVY. PME is the repository of physical parts in the ship, organized in a logical manner. For the Pilot, PME was organized in the Generic Product Work Breakdown Structure,[11] which breaks the ship down according to system, construction block breakdown, and worktype. A piece of deck plating would exist as an entity in PME, with attributes about the weight, center of gravity, surface area, thickness, material type and so forth. In the last stages of ship design, the entities of the ship are well known and modeled. In the earliest stages of ship design, the entities are less concrete. PME addresses the uncertainty in two ways. First, a collection of entities can be entered as an aggregate, or collection of items, without being placed individually. Second, an entity can be entered into PME manually, before it is modeled in the CAE system. When the entity is finally modeled in the CAE system, the exact attributes can be posted back to PME. MAAST engineers used Intergraph's CAE tools, the Integrated Ship Design Product software, ISDP. The Virtual Design Review software was also from Intergraph; Collaborative

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[10] Two examples, picked at random, are Windchill and ProjectWise.

[11] Koenig, et. al. "Towards a Generic Product-Oriented Work Breakdown Structure for Shipbuilding," SNAME Ship Production Symposium, 1997.

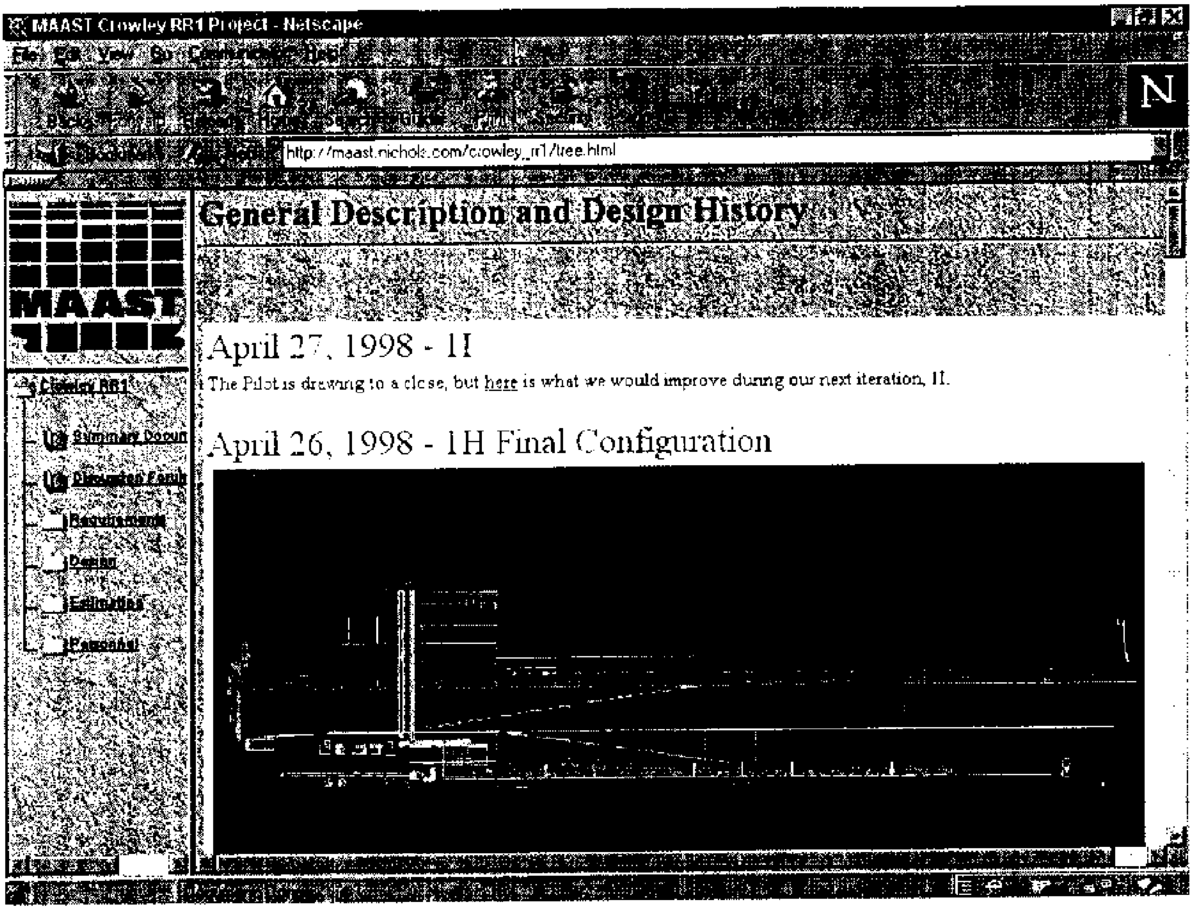

Figure 6: General Description and Design History

MoDel Review, or CMDR. CMDR presents the same graphical view of the ship as in the ISDP environment, but in a read-only way, much as if a VRML file had been made of the 3D CAE model. Because of this, the CMDR view of the ship is less data-intensive and less demanding of the system hardware. CMDR allows for simultaneous viewing of the model from multiple distributed sites, a feature used on multiple occasions during the Pilot. Files of walkthroughs can also be generated, to create a permanent record of the configuration. MAAST Pilot walkthrough files were typically 3-5 Mb in size. Output such as walkthrough files were generated in formats suited to broad access via the Extranet. Future applications will incorporate automatic posting of such files to the site, ensuring that the latest model is represented. CMDR was an easy way to let the customer see the 3D CAE ship without having to buy and learn how to use the CAE software.

Beginning of the Pilot

On March 11, two members of the team flew down to visit with Norman Gauslow in his Jacksonville office to begin a design exercise referred to as the Pilot. This travel period would prove to be the last major bit of travel performed during the Pilot.[12] At the end of a two-hour meeting, they had a list of one page of requirements for a ship carrying 170 trailers at 17.5 knots. This was the

[12] The only trip taken after this initial visit was when an Intergraph person visited Crowley in Jacksonville, to help install a new version of the CMDR software.

starting point for the design. The team initially explored four designs, two with Integrated Electric Drive and podded propulsion, one low speed diesel, and one medium speed diesel. The group pursued the four different solutions in a parallel fashion, as part of an effort to experiment with set-based design.[13] In set-based design, the team pursues several design concepts in parallel, without locking into any one design too early. Common elements were included in all configurations. Even if one design is initially promising, the set of designs is pursued until the options clearly prove their merits. This gets away from the design spiral mentality. Web enabled management makes true parallel, collaborative design possible for virtual enterprises even when participants have differing levels of capability and hardware.

Customer Influence

A revolutionary aspect of web-enabled management is the constant and rich communication between the customer and the team. The team gets quick resolution and clarification on requirements issues and continual feedback about the direction of the design. The customer gets continual reassurance that the design is proceeding well and in the right direction. If course corrections need to be made, they can be made earlier, where they are cheaper, instead of later. This continual reassurance is much different from delivering a paper ship or proposal at the end of the effort. The team is designing "his ship" from the start.

During the first three weeks of the Pilot, the team evolved the initial configurations into feasible concepts. At this time, the medium speed diesel option became the leading concept. Though the customer had been following the discussion groups and the website, the comments had been more inquisitive than requests for change. However, the ship largely reflected the team's solution to the design problem, and not the customer's. This changed at the first virtual design review. The first design review was supported by a conference call among the team, while looking at the website. The website had a set of documents and pictures that collectively described the ship. During the three hour conference call, there were 32 comments by the customer, of which approximately half were comments that affected or changed the direction of the design. It was this type of feedback through three virtual design reviews that made the final ship design into a shared solution, better than any one participant could have created.

The MAAST infrastructure made it possible to respond quickly when the customer decided to influence the design. Figure 7 shows the configuration of the deckhouse during the first design review and during the wrap-up session. Perhaps most striking is the refinement in the product model over the last three weeks of the Pilot. Further, the deckhouse has been elevated in the second screen capture. During the first design review, the customer requested that the deckhouse should be elevated, to more efficiently make use of the weather deck. Working through the website discussion groups, the team arrived at a new wingwall configuration, uptakes and ladder arrangements that met the structural and stability considerations.

The final arrangement of the ship is shown in Figure 8. The characterization of the design included hullform geometry (developed using FASTSHIP); structural modeling of all plate, stiffeners, and major openings (no end connections or details); cargo hold arrangements, including 3-D stowage plans for required loadouts; modeling of all major cargo access equipment; cargo hold ventilation systems; cargo hold fire protection systems; wheelhouse configuration, including 3-D layout of integrated bridge equipment; deckhouse space arrangements in 3-D; Main Machinery Space arrangements (3-D envelopes of major components); and supporting naval architectural and marine engineering calculations.

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[13] "The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster," Ward, et. al. Spring 1995, Sloan Management Review. http://mitsloan.mit.edu/smr/past/archive/smr3634.html

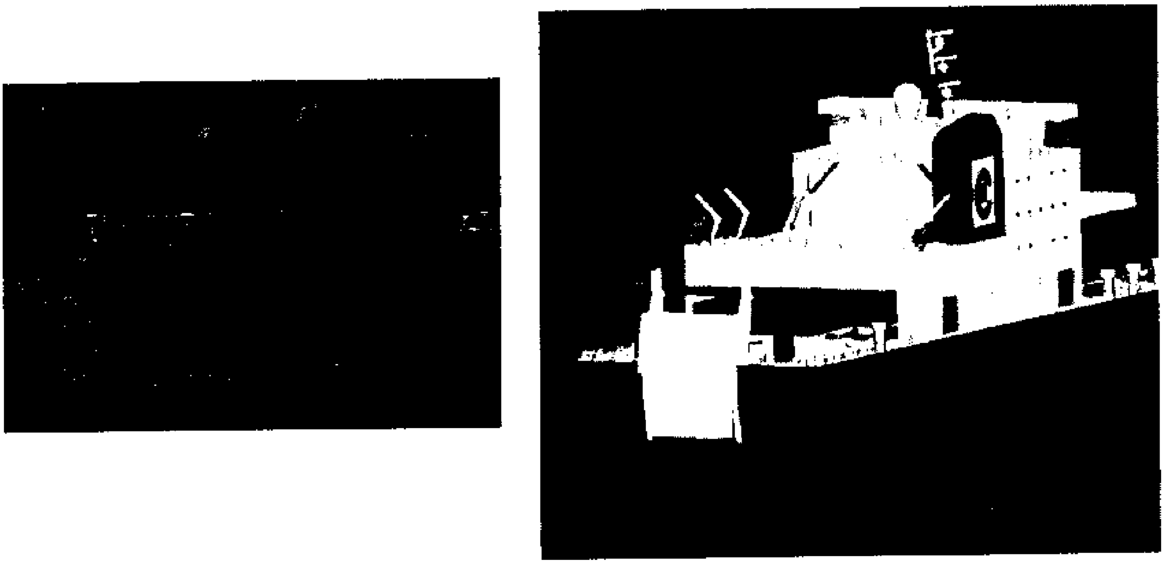

Figure 7: Customer Driven Change

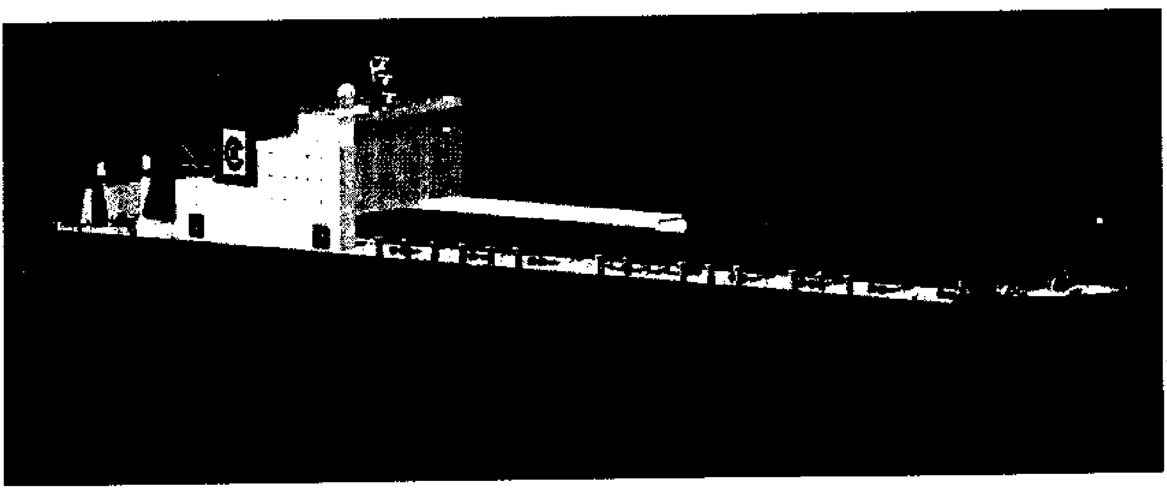

Figure 8: Final Product of the MAAST Pilot

Current and Future Work

After completing the MAAST project we have continuously sought to apply the techniques of web enabled management to other projects. We have found applications both internally and externally: identifying applications where the approach would improve our own productivity; and finding customers with projects for which we could establish and maintain the infrastructure for more effective management.

Within Nichols Advanced Marine we are applying web management techniques to project management of software tasks. Multiple individuals in more than one department are involved in a series of software development tasks. These include tasks for outside customers and internal I.R.&D projects to develop software for the open market. Nichols follows a rigorous Software Product Improvement Program for such tasks and managing resources for the tasks is a key element of our Software Process Improvement Plan. Using web enabled management, the participants and line managers can access information on resource assignments and schedules. Software requirements documents, specifications, and other SPIP documentation is readily available. Interaction on related issues is organized by secure newsgroups. Regardless of organizational boundaries, software engineers can view management information. Division managers can audit task status and evaluate backlog for planning purposes. As this project demonstrates the advantage of the approach, we expect to see other parts of our organization use web enabled management to coordinate projects.

The U.S. Navy is a vitally important customer for the authors. We are involved in early stage concept design development for a number of ship types. On one project, we are creating a web based infrastructure to manage ship requirements and concept descriptions. Many government representatives require access to the information as well as having an interest in the concepts generated. The web based approach provides a convenient means of managing the information and providing controlled access. The United States Coast Guard Deepwater project is a significant undertaking. Currently, three teams are under contract to develop concepts in response to Deepwater requirements. In addition, the Center for Naval Analysis is developing concepts. All four teams must produce the required design products in response to the USCG requirements. A team of USCG engineers must evaluate the responses and provide direction. A web enabled management approach has great potential in this acquisition program. The four teams are required to maintain websites and post specific information for USCG review. Superimposing a web enabled management system above these contractor managed sites will facilitate efficient evaluation and comparison of the parallel efforts.

Conclusion

Web Enabled Management is the process and business changes that take advantage of current technology. Proper Web Enabled Management addresses:

- Customer Presence
- Leadership, Execution, and Accounting
- Membership
- Parallel Design
- Online Reputations
- Scalable Architecture
- Security
- Configuration Control
- Document Management
- Support Project from "Lust to Dust"

Businesses involved in shipbuilding invariably have a fundamental computer capability that is sufficient for the proposed web enabled management techniques. Today's shipbuilding marketplace demands cooperative efforts between organizations. Web enabled management techniques improve the formation, integration, and design efforts of these enterprises. Web enabled management can become the means for orchestrating the virtual enterprise. The challenge is not in developing the technology for this purpose but in changing processes to use technology effectively.[14]

[14] "CEO Hatim Tyabji is an avowed technologist. Yet he insists the key to success is '5 percent technology, 95 percent psychology and attitude.' That is, a company can spend a king's ransom on 25,000 Lotus Notes licenses…but that still doesn't mean that there will be any form of automatic sharing of information." Tom Peters, The Circle of Innovation, Alfred A. Knopf, Inc, 1997.

ENHANCED INFORMATION FLOW IN A MID-SIZE SHIPYARD: A CASE STUDY

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Abstract

Today's mid-size shipyards depend more and more on computer-aided approaches to shipbuilding. Not only is this found in the areas of design and engineering, where CAD/CAM systems are widely accepted, but also in areas such as marketing, sales, estimating, materials management, production control and production. One commonly sees computer-aided approaches in at least several areas of virtually all competitive mid-size shipyards. These yards continue to advance technologically, and at least some have embarked on the next step, which is to enhance the flow of information from one area of the shipyard to another in a standardized, integrated manner. While a fully integrated, electronic system with a single database may be the ultimate vision, most yards' present goals are more modest, though nonetheless capable of dramatically enhancing the flow of information, and in turn improving yard productivity. This paper presents a case study of information flow at Alabama Shipyard, a mid-size U.S. shipyard. Included is a description of information flow needs, the resulting computer-aided systems, and examples of information flow paths.

Introduction

While large shipyards have depended on computer-aided approaches to shipbuilding for many years, only recently have most U.S. mid-sized yards started to introduce such systems. Typically, these yards begin the process by implementing computers into payroll and accounting. Then they adapt computer-aided design (CAD) for developing 2D drawings in the design department. The more advanced yards now use 3D "product model" systems in their design and engineering departments, and other sophisticated, computer-aided software in areas such as sales and marketing, materials management, estimating, production control and production. At times, these systems are developed in house, but often they are commercial off-the-shelf systems that meet the needs of shipyards.

This paper addresses computer-aided shipbuilding from the perspective of information flow in a mid-size shipyard. Information flow implies a certain level of integration. One may view integration as being in four levels:

1. Manual Integration – The results of one software program (e.g., CAD drawings) must be keypunched to another program (e.g., bill of materials). In reality, there is "no integration."
2. Module Integration Various modules of a program share data with one another. For example, hull form data is communicated to the module that calculates ship stability. User interfaces may differ from module to module, and commonly this type of integration cannot support combining results from among the various modules to make a unified presentation.

Often, interfaces must be specially tailored and data conversion from one module to another may be difficult. A program with this level of integration is sometimes characterized as an "interfaced" system rather than an "integrated" system. Typically, each module has its own database.

3. Product Model Integration A more advanced level of integration is by means of a product model, a detailed, 3D description of the ship and its major systems. The product model has a common database that is shared by all the modules; that is, there is no need for data conversion among the modules.
4. Enterprise Integration – More advanced yet is integration of the design, engineering and construction aspects encompassed with the product model program with other programs addressing areas such as management, accounting, business development, human resources, and entities outside the shipyard. Enterprise integration may focus on a single shipyard or may extend to several shipyards and their associated vendors, customers and regulatory organizations.

This paper addresses integration at the fourth level, Enterprise Integration. In this case, the enterprise is defined to be a single shipyard at the departmental level of detail. General aspects of information flow are discussed, followed by a discussion of the specific case of Alabama Shipyard, a new construction yard located in Mobile, Alabama.

Information Needs

Within a shipyard, different departments have vastly different information needs. For example, the sales and marketing department needs only a summary specification and a limited set of drawings of a ship in order to approach potential customers, yet the production department needs a complete definition of that ship, and also scheduling information. One can view this in a simplified way by examining information needs of six typical shipyard departments:

- Sales and Marketing
- Estimating
- Engineering
- Materials Management
- Production Control
- Production.

Typical information needs for these departments during the conduct of a ship construction project may include the following:

- Sales and Marketing – Ship information at varying levels of detail (concept, contract and detail designs) for marketing meetings, negotiations, and contract signing with the owner
- Estimating – Ship information on hull and outfit at varying levels of detail during the ship design process
- Engineering – Owner's requirements, owner's feedback during design stages, and production input (to help make the design easier to produce)
- Materials Management – Ship information on hull and outfit to a level of detail sufficient to place orders with vendors and subcontractors
- Production Control – Ship information, owner's schedule constraints
- Production – Ship information, schedules, work packages, and materials.

These six departments may participate in a ship construction project by means of the following 14 steps:

1. Initial Discussions with Owner, carried out with standard shipyard brochures, example design documents and on the "back of the envelope"
2. Concept Design Development, using input from initial discussions and information from past similar designs
3. Initial Estimate, based on information gleaned from the owner and from the concept design
4. Further Discussions With Owner, with the concept design and initial estimate as a baseline, resulting in owner commitment and further design direction
5. Contract Design, carried out to a level of detail sufficient for a fixed price agreement between the shipyard and the owner
6. Materials Cost Estimate, based on the contract design
7. Production Cost Estimate, for facilities and labor, based on the contract design
8. Contract Cost Estimate, reflecting the information contained in the contract design
9. Sign Contract at a price reflecting production and cost estimates
10. Detail Design Development, carried out to a level of detail sufficient for development of bill of material, production schedules and work packages
11. Production Input to the detail design, to help make the design easier to produce
12. Materials Order, based on the detail design
13. Scheduling and Work Packages to reflect the detail design
14. Construct Ship, using the schedule and work packages.

The information inherent in these 14 steps flows between departments as shown in Figure 1 (in actual practice, departmental organizations vary among different shipyards; thus, the six departments of Figure 1 may be thought of as "shipyard functional areas"). The six departments are listed along the top of the figure. Below the departments are their relevant ship construction steps. Each step is connected to the next, showing the flow of information from department to department as the project matures from initial discussions with the owner to actual construction of the ship. In this example, not all shipyard departments and functions are included. For instance, contracting and upper management participation in negotiations with the owner are omitted for simplicity, and folded into Sales and Marketing.

The information flow is shown in a different manner in Figure 2. While Figure 1 illustrates the timeline, Figure 2 highlights the fact that all six departments are linked during the various steps of the ship construction process. Although this figure is rather simple, one can easily imagine the case in an actual shipyard, where information flow among these and other departments is much more complex.

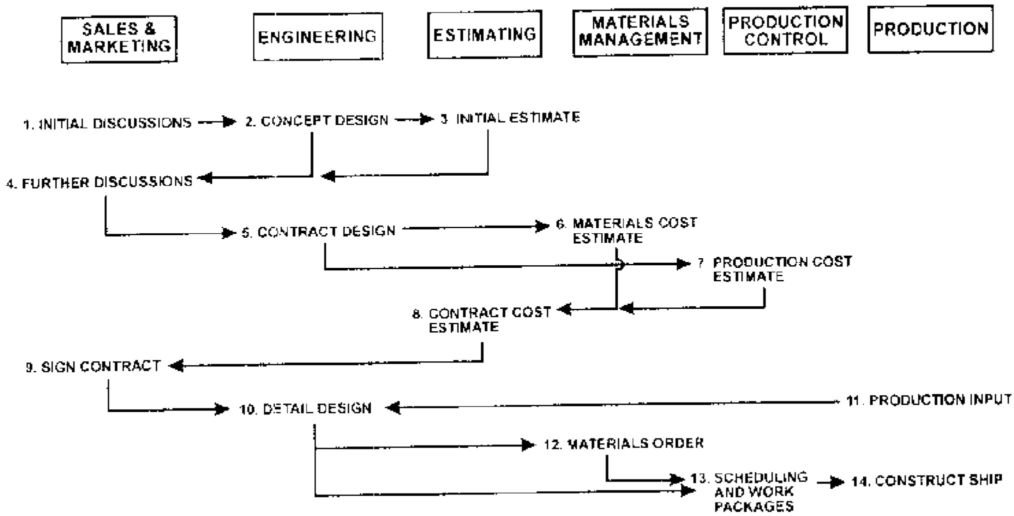

Figure 1. Sequence of Information Flow Between Departments During a Ship Construction Project

Computer-Aided Information System Needs and Challenges

The information flow described in the previous section has traditionally been achieved through methods involving manual transmission of information from one department to another, manual reformatting to meet the particular needs of each department, and a resultant loss of time and often a loss of information where it is most needed (such as which drawing issue is pertinent for construction).

There are a number of general needs of a successful computer-aided system for enhanced information flow, including:

- Compliance with industry standard interface and data exchange formats, such as ANSI, SQL, MAPI, TC/IP, CORBA, and ODBC.
- Easy integration with legacy, best-of-breed, and third-party software products
- Operation in a "network centric" and "data centric" environment, that is, sharing data throughout the shipyard with easy access for all authorized users
- Ability to use imaging for documents not received by the shipyard in electronic format, such as certain Receiving and Accounting documents.

Unfortunately, there are important potential pitfalls inherent in moving from a manual to a computer-aided system for information flow, including:

- Different Information Needs from One Department to Another for the Same Material For example, the Materials Management Department is interested in tracking gross steel plates, the Engineering Department is interested in tracking the piece parts resultant from those plates, and the Production Control Department is interested not only in tracking the plates, but also the resultant panels, subassemblies, assemblies and blocks.

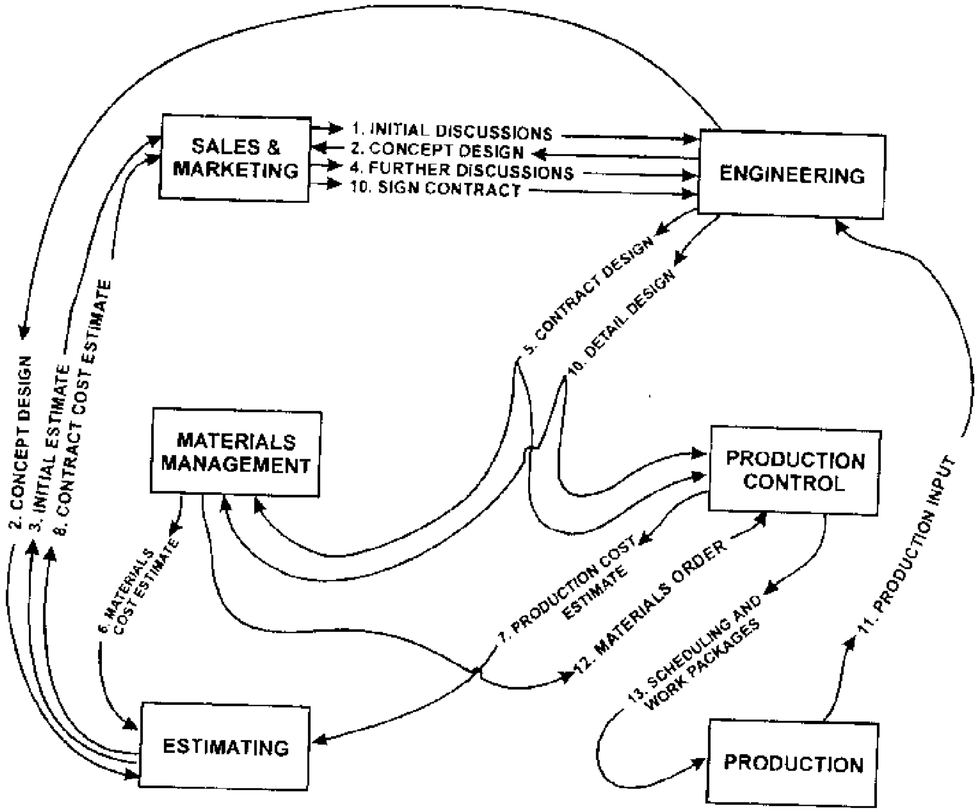

Figure 2. Information Flow Between Departments During a Ship Construction Project

- <u>Different Software Among Different Departments</u>, some of which may be quite sophisticated (such as a product model CAD/CAM/CAE system in the Engineering Department) and some quite simple (such as a spreadsheet program for the Estimating Department to make an initial estimate of ship cost), and which often cannot readily exchange information.
- <u>Different Hardware Among Different Departments</u>, again, some complex and others basic.

The considerable challenges of developing a successful flow of information among different computer systems are reflected, for example, in the necessity of addressing possible inconsistencies in semantics between the "same" data located in multiple databases. At least eight such inconsistencies may arise [1]:

- Name conflicts
- Data type/representation conflicts
- Primary/alternate key conflicts
- Referential integrity behavior conflicts
- Missing data and null values
- Level of abstraction
- Identification of related concepts
- Scaling conflicts.

Much work has been and continues to be carried with the goal of improving integration. Representative examples of such efforts include STEP (STandard for the Exchange of Product Model Data), SEASPRITE (Software Architectures for Ship Product Data Integration & Exchange), MariSTEP and MARIS. Progress has been made, but for most applications in today's U.S. mid-size shipyard, integration is an exercise requiring care and resources. Fortunately, integration at a useful level is within the realm of practicality.

Elements for Enhanced Information Flow

Enhanced information flow at practical level may be carried out by integrating the following elements:

- Sales and Marketing Support - A Sales and Marketing Support System includes contact management and a number of databases containing information about potential customers, such the status of their fleets, shipping lanes, and economic trends in their businesses. Input comes from external references such as Lloyds Registry and from direct contacts with existing and potential customers. Besides customer information, this database contains shipyard production capacity information (e.g., construction capacity, dock availability).
- Product Model -- A product model program supports the analysis and informational needs for the engineering, design, construction and maintenance of a ship. The product model database contains 3D geometric information such as hull form definition, and non-geometric information such as equipment weights. The information is contained in a central database and is available as graphical displays, hardcopy printouts, and as electronic files for use by NC production equipment. The database provides a single source for complete, updated and consistent information to all involved in the design and production processes [2, 3]. Ship design and production information flows from the product model to the six departments as shown in Figure 3.
- Bid and Estimating System -- A bid and estimating system supports the company's need to furnish a potential customer with a highly reliable, low-risk bid quotation based on information supplied by the customer (e.g., ship dimensions, cargo capacity, ship speed) and the concept design from the Engineering Department. The computer-aided Bid and Estimating System is parametric, and estimates costs for material, labor and subcontractors.
- Project Management System – A Project Management System supports the planning and execution of the ship build strategy. It assists in the management of materials, subcontractors and production personnel by a set of schedules and plans. The schedules and plans are tiered in several levels of detail. Figure 4 shown information flow associated with the Project Management System.
- Business Information System - The Business Information System is comprised of modules to assist in areas such as payroll, human resources, personnel, general ledger accounting, fixed assets, accounts receivable, accounts payable, financial reporting, job cost, purchasing, and receiving. Major areas of information flow to and from the Business Information System and the six example departments are shown in Figure 5.

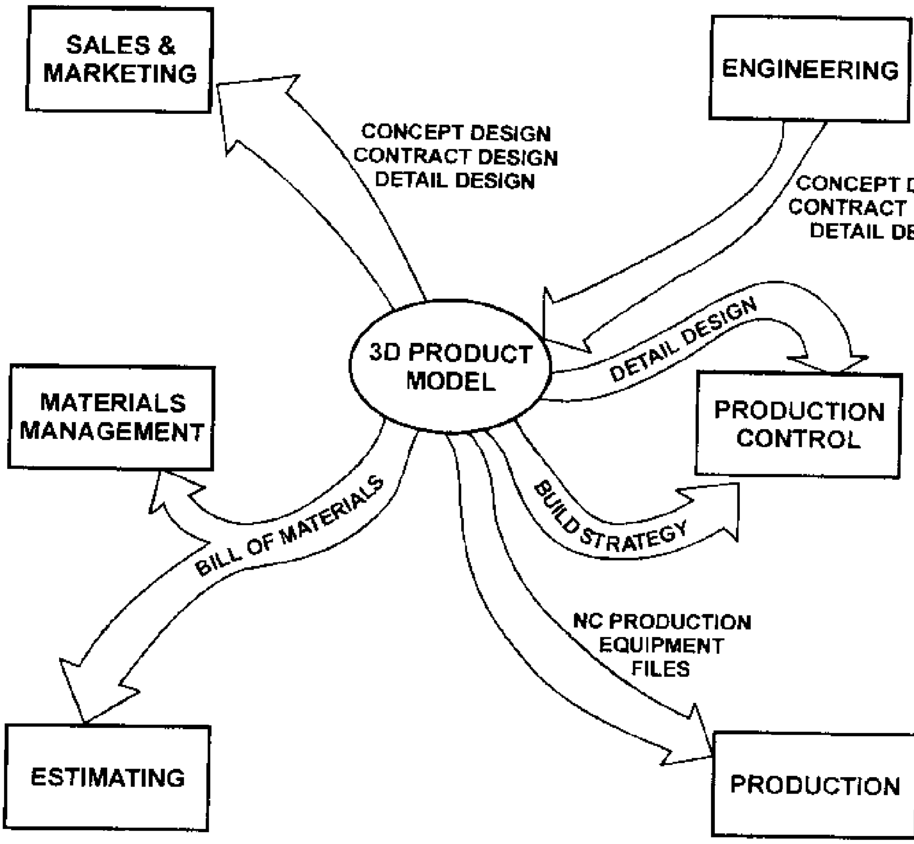

Figure 3. 3D Product Model and Enhanced Information Flow

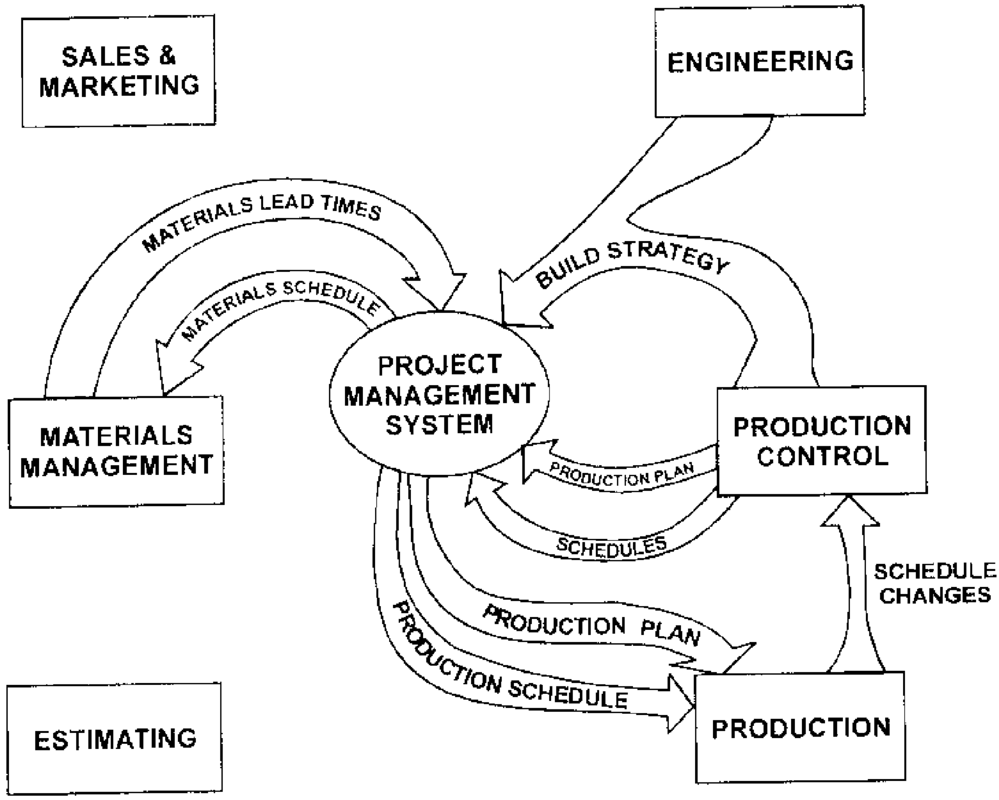

Figure 4. Project Management System and Enhanced Information Flow

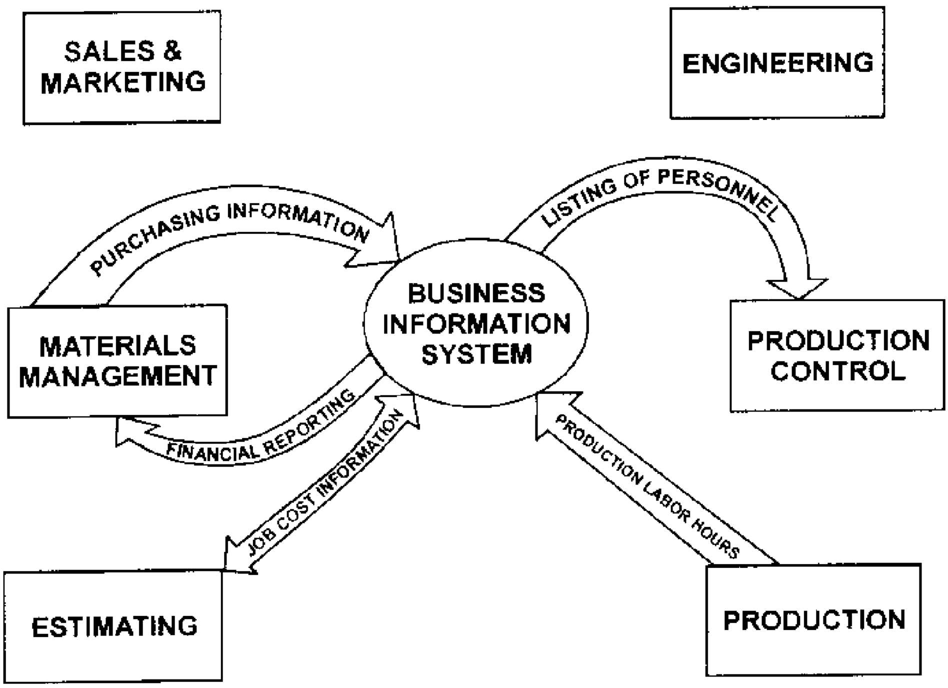

Figure 5. Business Information System and Enhanced Information Flow

- Workflow Module – A Workflow Module (normally part of a larger system) has the ability to exchange, track and control working documents (e.g., payroll, financial reporting, engineering change orders) among shipyard departments. Because workflow is integral to the ongoing functioning of the shipyard, the computer-aided system must be consistent, accurate, and well documented. Figure 6 illustrates an approach to workflow for affected example departments.
- Document Control System - Document control is the ability of the shipyard to control the massive accumulation of documentation associated with the marketing, design, engineering, materials management, planning, and construction of a ship. Importantly, a computer-aided Document Control System helps ensure that only the current versions of documents (including drawings) are used in the shipbulding process.
- Imaging System – Imaging software and hardware are used to record, file and retrieve digital electronic images of shipyard documents, including drawings, requisitions, purchase orders, receipts, schedules, estimates, specifications, manuals, instructions, and drawings. In certain situations, the Imaging System may not directly store images, but will serve as a central clearing house for queries and retrieval (for example, with ship drawings, which may be stored in the Product Model database). Figure 7 depicts information flow to and from an Imaging System.
- Electronic Data Interchange -- Electronic Data Interchange (EDI) is mainly used to communicate with organizations outside of the shipyard, such as customers and vendors. EDI is typically handled through a third party that provides a "store and forward" delivery

service for packets of information (e.g., specifications, requests for quotation, purchase orders, and drawings).

- Internet/Intranet -- While EDI is used primarily to communicate packets of information with external organizations, the Internet and the Intranet are used for shorter, more informal, and person-to-person communications within the shipyard (Intranet) and outside the shipyard (Internet). In recent years, the Internet is assuming more of the role traditionally held by EDI, while the Intranet (Figure 8) is augmenting telephone communication, paper memos, and face-to-face meetings.

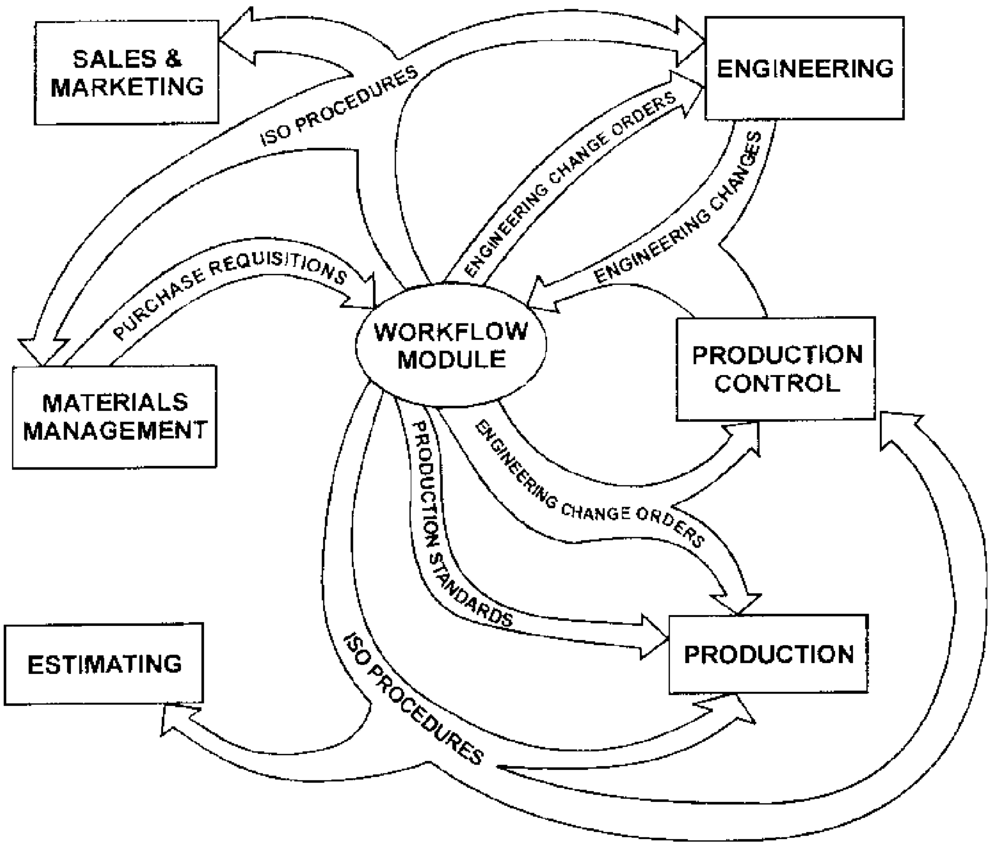

Figure 6. Workflow and Enhanced Information Flow

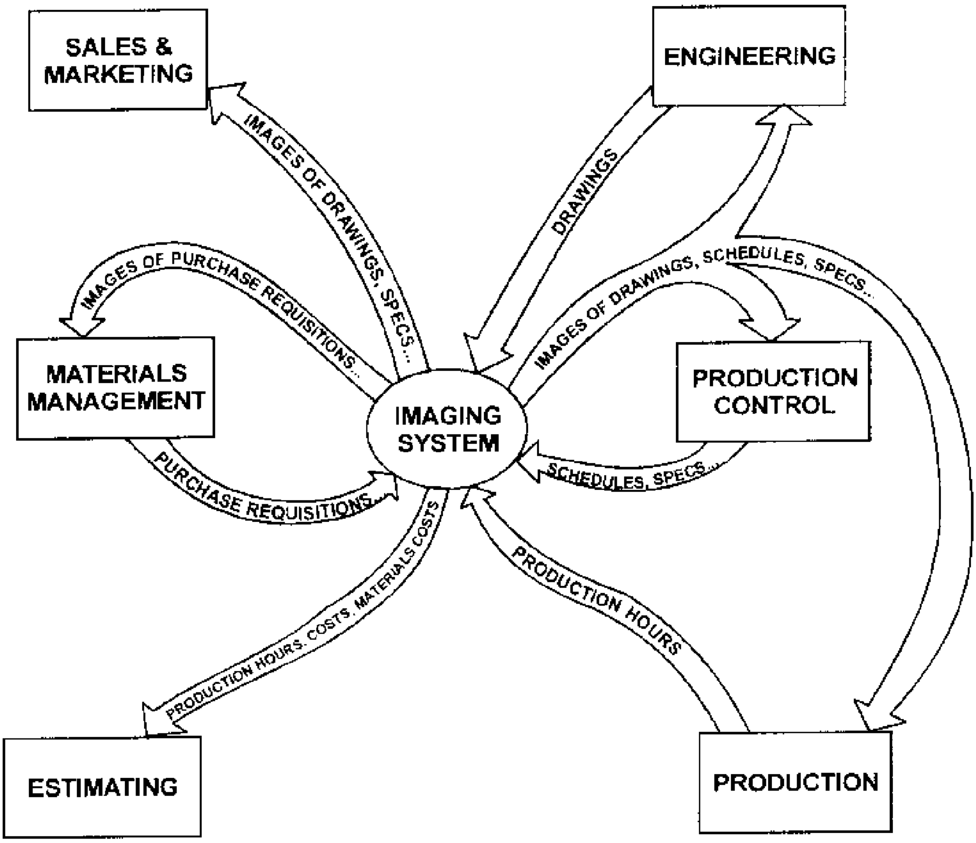

Figure 7. Imaging and Enhanced Information Flow

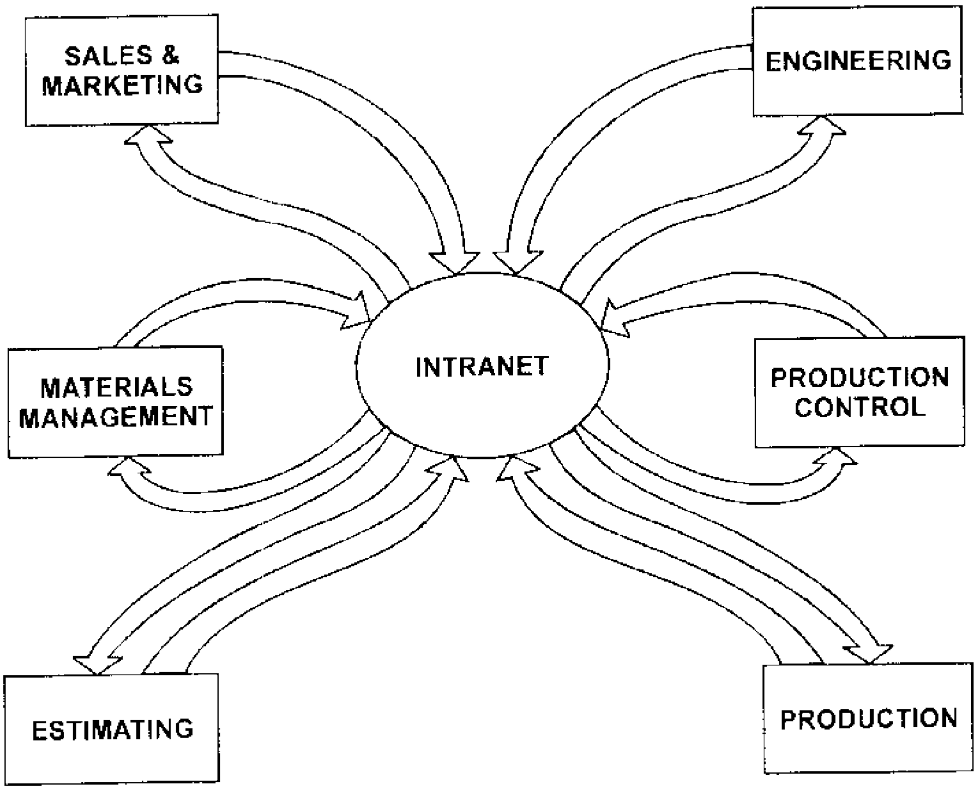

Figure 8. Intranet and Enhanced Information Flow

Enhanced Information Flow Case Study

Alabama Shipyard (ASI), a mid-size newbuild shipyard located in Mobile, Alabama, serves as a case study for enhanced information flow. This yard, presently undergoing a multi-year modernization program, has made substantial progress toward implementing elements of enhanced information flow. ASI has learned that commercial software is responsive to the needs of enhanced information flow, but an entire information system is not available from a single vendor (notwithstanding the enthusiastic claims of certain vendors). Each vendor is an expert in its own field, with some overlap among fields. There is sufficient overlap to interface the various major systems, although the interfaces usually must be tailored to the specific information exchange needs of the shipyard applications.

ASI has learned that a standardized infrastructure of common hardware and software can address nearly all of the needs of the different departments. There is a small sacrifice in functional capability for certain specialized users but this is more than counterbalanced by tremendous gains by avoiding interface mismatches between different hardware and software systems. The Information Services Department analyzed the connectivity and information needs of the various ASI departments and established standards for hardware, software, and networks. The resulting infrastructure provides all departments with access to shared hardware resources such as the main host computer (an IBM AS/400), file and mail servers, CD reference libraries, standard operating procedures, ISO procedures, manufacturing standards, modems, Internet service providers, and imaging services. The network is managed by an MS Windows NT® network operating system and is linked with a combination of fiber optic and category 5 cabling.

The AS/400 computer was selected as the host computer because it is certified to be year 2000 compliant, can support the yard's present host-based needs, and can support the projected client-server applications. The AS/400 is electronic commerce enabled for Internet applications. In the future, ASI hopes to equip production personnel with web browsers capable of accessing the Internet to retrieve drawings from the yard's FORAN CAD/CAM/CAE system. The yard also plans to obtain the capability to use hypertext to allow a user to click on a reference to a standard procedure (e.g., end cut detail for a structural profile) and have the browser open the most recent version of the procedure.

The following paragraphs address particular applications that address major elements of enhanced information flow. Most of these applications are already in place and functioning at the shipyard.

- Sales and Marketing Support – Sales and Marketing personnel use Personal Data Assistants equipped with Windows CE® to maintain connectivity to electronic mail, electronic calendars, and contacts when away from the office. In some cases, their Outlook® databases have been enhanced with additional fields tailored to support their sales efforts. Future integration with production scheduling is planned to provide updated resource availability, and to provide access to documents such as Lloyds Registry and the Thomas Register.
- Bid and Estimating System – ASI is investigating commercial software to support the bid and estimating processes. Present candidates include the Mc² system from Management Computer Controls, Inc., and the Esti-Mate system from SPAR Associates. Presently, an Excel® spreadsheet using a complex set of macros is used to develop estimates. These are then re-entered into the Business Information System to track estimates to actual costs. ASI estimators are presently satisfied with their Excel® spreadsheet solution. A near-term future step is integration of the spreadsheet with the Business Information Systems for direct information flow.
- Product Model – The shipyard uses the FORAN 3D CAD/CAM/CAE product model program for computer-aided design and production. FORAN provides graphical displays and hardcopy drawings to support the production crafts, and electronic files for NC production equipment. The shipyard plans to link the FORAN database with the Project Management System (for build planning and scheduling) and the Purchasing System (for bill of materials).
- Business Information Systems – Payroll, human resources, personnel, general ledger accounting, fixed assets, accounts receivable, accounts payable, financial reporting, job cost, purchasing, and receiving are all addressed by software from J.D. Edwards Enterprise Solutions. The shipyard has acquired the J.D. Edwards World software. This is essentially an IBM AS/400-based system with a graphical user interface (GUI) placed over the standard "green screen" user interface, resulting in a system with Windows® type features. The shipyard plans to upgrade to the One World version of the software. One World is a client-server-based set of Business Information Systems with a native GUI. It may also be used

through the Internet or intranet, enabling One World to take full advantage of files created and stored in the Imaging System and the Document Control System. This software is equipped with application program interfaces (APIs) to accept data from many of the components of ASI's enhanced information flow systems, including the Project Management System, Product Model, and Estimating.

- Project Management System Alabama Shipyard uses Primavera® software for scheduling, as well as MS Project® with the Pro Chain® add-on. In the near term the shipyard will select one of these systems for use, and develop interfaces to the J.D. Edwards software.
- Work Flow -- When implemented at ASI, the One World software will include a Work Flow module. Work flows are provided to control purchase requisition approvals and other standard work flow business functions. The Work Flow module allows users to develop their own work flows, with simple-to-use tools. Custom work flows may be developed to support engineering change control, ISO procedures, production standards development, and other functional flows. The Work Flow module uses MS Exchange® electronic mail for handling work flow notifications, saving the user from having to log on to a separate electronic mail network.
- Imaging System – The OTG® Imaging System is used at ASI, allowing document scanning for future retrieval from server-based disks, Write Once Read Many (WORM) disks, optical storage, and other media. This system provides the shipyard with a huge capacity for the storage of information, including work papers, spreadsheets, testing procedures, drawings, and specifications. In addition, the software is used to scan hardcopy documents and store the results as MS Word® documents. One World has the ability to retrieve documents under the control of the Imaging System.
- Document Control -- While the Imaging System provides limited revision control, the best solution is to obtain a dedicated system. The shipyard is considering PC Docs from PC Docs, Inc., and FileNet from FileNet Corporation.
- Electronic Data Interchange – To date, Alabama Shipyard has not had a need to communicate with external entities through EDI. Instead, electronic facsimile direct from the IBM AS/400 has been a suitable substitute.
- Internet/Intranet -- Every workstation at ASI has access to the Intranet. Selected workstations have access to the Internet. Alabama Shipyard's use of an Internet service provider has proved to be a savings over dial-up Internet access. The shipyard hosts a home page with hyperlkinks to job postings. J.D. Edwards One World uses the same Internet connection to allow direct access to web sites electronically attached to records in its Business Information System.

Conclusions

Information flow, always a need in shipyards, is of ever increasing importance in today's global, competitive shipbuilding and ship repair community. Enhanced information flow is key to decreasing cycle time and decreasing rework while increasing the efficiency by which shipyard departments work together. This paper has set forth examples of the needs of shipyard communication and has introduced a vision of such a system, using today's technology in a practical manner. In particular, the Alabama Shipyard case study has proven that mid-size shipyard integration can be achieved through careful planning and the use of off-the-shelf commercial software. The key to success is to build the right infrastructure and to select modular components from vendors who understand their core competencies and limitations and who plan for integration with other vendors.

Acknowledgments

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A CAD BASED GENERIC FRAMEWORK FOR DESIGN FOR PRODUCTION

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Abstract

How well shipyards implement the design for production philosophy influences shipbuilding efficiency. Design for Production is the extent to which the product is designed for ease of production. It is employed throughout the ship development cycle, starting with the shipyard's preliminary build strategy to information evolving after detail design, to ensure the best compatibility to the production facility.

This paper presents a generic framework necessary to implement design for production in a CAD design environment. The critical information modules are presented as in a common product information database. Highlights are the module for data exchange that enables total integration. As is reported in the updated Design For Production Manual, the approach to early incorporation of these principles in design involves the development and evaluation of common generic blocks. Discussion, including future directions, is provided to enable mass customization by developing necessary techniques in conjunction with a CAD system.

Introduction

CAD/CAM/CAE development is one of many attempts to enhance the design process by providing the capability to generate, utilize, store, and transport design information electronically. CAD/CAM/CAE technologies were first applied in shipbuilding in the late 1970s, starting from a manual drawing (2-dimensional sketch), to a 3-dimensional scale model, to a CAD/CAM system data exchange, with the primary purpose of transferring design information to production. Since then the CAD/CAM system has grown from 3D-product draft to 3D-product information model. The product information database is a system that not only has geometric entities, but also contains non-geometric information, such as material, connectivity type, production schedule, etc. To be competitive, shipbuilders must now move in the direction of use of a product information database.

The production information database (Figure 1) is a single database, which can be considered to act as an incremental knowledge base system for producing the ship. It is responsible for containing all design, production and other relevant information. There are two fundamental approaches of developing a common product information database. The first is the neutral data sharing approach, where all types of information are managed in a centralized database. This approach has the advantage of minimizing the amount of data transfer because there is less network connection. Information accessing is also consistent because the exact same database is shared. The shortcoming of this approach is the difficulty of implementing future upgrades. To add another type of database, for example, will require a major effort. This approach requires implementing a central database. It's also possible if all the applicable databases share the same data scheme. The second common product information database scheme involves a direct networking approach, where an interface is needed for each database pair. This approach has more flexibility in terms of system modification. However, it is difficult to maintain system integrity because of the numerous interfaces.

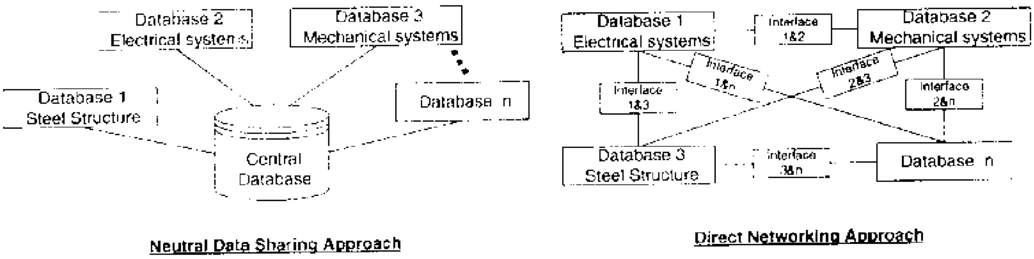

Figure 1. Common Product Information Database

This paper describes a general framework for a product information database that supports design for production. The critical elements are described as a CAD module. The paper is organized as follows. First there is a brief review of product information databases. Next, the recently published design for production manual is briefly summarized, and the implementation of design for production in a CAD environment is explained. Then, the CAD components needed to achieve the design for product philosophy are presented. Tool management, the integration module, and data exchange standard management are highlighted. Lastly, a discussion of future research on identified standard components at the block level is provided, including a recommended approach for handling product variety. The notion of the common generic block (CGB) is presented and proposed for utilization in the CAD environment.

Product Information Database: A Review

Work done by Pederson and Hatling [1] describes a CIM solution at the shipyard and information complexity in ship production. The authors started by identifying necessary information and pointing out the need to optimize the use of information technology in order to balance the information flow, how to "reuse and update" the product information database. Requirements identified include management structure for the success of CAD/CAM integration and the necessity for a single, yet complete, product information model database. Similar work with regard to studies of product information models is also reported in Johansson [2].

There are numerous case studies reported from practical implementations. These papers reported the benefit of implementing product information database technology in two contrasting projects [3]; one was a shipbuilding project in a small shipyard and the other was a ship conversion project in a large shipyard. Lessons learned indicated the success and capability of the U. S. shipyards in implementing product information model technology even though these yards are using typical production technology, not leading edge automation. Another similar work [4] emphasizes the role of CAD/CAM/CAE in shipbuilding by reviewing the contribution of computer applications to ship design and production, based on the experience of an engineering company with several shipyards during a concept design and detail design. It stresses the importance of corroborating more design details earlier, by taking advantage of new technology. Information needed for design and process design should be available during all the ship design life cycle. From the author's design for production philosophy, every necessary document for each design task is identified.

Delius [5] reported that in order to provide the means to implement design for production in shipbuilding, emphasis must be placed on management reorganization. The strategy proposed was to gradually implement the system, especially for a shipyard with a limited amount of computational resource. He characterized the working methods in a small shipyard and proposed steps in installation strategy for a product information model, including integration for using a CNC automatic cutting machine, for structural parts, and to integrate 3D modelling with total outfitting. A case of a small shipyard was presented [6] using team-building techniques to integrate CAD, NC Cutting, and Numerical Control Lofting with production. The use of performance-based management, the use of process management techniques and the result of productivity improvement are reported. Bles presented [7] another case study of the success of implementing CAE/CAM in a small shipyard using a product information model, the NUPAS system, at Engineering Centrum Groningen B.V.

VanDevender [8] presented research in shipbuilding design organization from a study at Ingalls Shipyard, Mississippi. They recommended a design organization in the form of a design/operation team, which includes naval architecture, marine engineering, and craft supervisors, etc. The project coordinator was assigned as a leader for information distribution. The benefits of this implementation included an increase in access of ship information and better instructions for manufacturing processes. Also addressed are the steps taken to increase effectiveness in design and production integration by using a product information model. The Mid-Term Sealift Ship Technology Development Program [9], conducted by NAVSEA with industry participation, identified four important requirements for the success of implementing a design for production philosophy. These include use of a generic build strategy, continuing the use of product work breakdown structure, implementing a production oriented cost-estimating model to optimize the use of resource, and development and application global standards.

Data Exchange Standard Management

Data exchange standards have existed in the marine industry for several years. Often, information is exchanged practically using neutral files, which mostly can be operated at a low level and can induce errors and inconsistency. There have been cooperative programs nationally and internationally attempting to standardize produce data models. IGES (Initial Graphics Exchange Specification), the most popular standard, is the standard geometric representation scheme. IGES allows multiple correct representations of the identical information, but lacks validation steps for translator and translation processes. Yet, because of the lack of capturing non-geometric entities, the evolution of product modeling evolved from IGES to PDES, which is mostly used for a feature-based product model. Additional progress has been made because of the need to incorporate non-geometric information in product information. STEP (Standard for the Exchange of Product Model Data) was first developed when a Navy Industry Digital Data Exchange Standards Committee (NIDDESC) began developing application protocols. This product of Navy/marine industry collaboration later became part of the STEP standards. The STEP Program was initiated in 1991 as a project to standardize product data structures to be platform independent. Although not new, ISO 10303 is still continuing to develop to include all the facets of product data. Examples of experimental standards for STEP are found in the NEUTRABAS and MARITIME projects.

The SEAWOLF project has made a significant contribution to design/production integration in shipbuilding and the use of a standard product model. SEAWOLF, a NAVY sponsored project, is the first full-scale project to use 3D solid modeling for production integration. Parts of the SEAWOLF project are presented in [10, 11]. The DDG51 Project [12] reported on a standard product model based on STEP protocols applied to this class destroyer. The NAVY developed the DDG51 digital translator to translate ship data between Computervision and Calma systems. DDG51 is reported as the first Navy ship designed and engineered totally in CAD.

Presently, each part of STEP is proposed and approved independently by ISO TC184/SC4 (Industrial-Automation Systems and Integration / Industrial Data). Background and progress of the development of STEP application in shipbuilding, along with the AP protocol initiative and approval, is presented in [13, 14, 15]. Current STEP status can be found in [http://www.nist.gov/sc5/soap].

Design for Production Philosophy

The traditional role of the ship designer is the preparation of an overall design of a vessel which will have a performance satisfying the owner's operational or functional requirements while complying with the statutory rules and regulations. The concept of design for production, however, requires that in satisfying these requirements, the ship designer must also give attention to ease of production. There are thus several major aspects to design, namely, design for performance, including design for safety and profitability and design for production. There are other aspects also, considered later in the development cycle, including design for overhaul, repair and maintenance. The overall objective of design for production can be defined as follows [16]:

> "Design to reduce production costs to a minimum, compatible with the requirements of the vessel to fulfill its operational functions with acceptable safety, reliability, and efficiency."

Clearly, there will be areas of interaction. The role of the ship designer can be seen in this context as one of arbiter, having the ultimate responsibility of deciding whether performance or production considerations shall take precedence in any particular case or of deciding the nature of the compromise to be reached. The organization of the design agents and shipyards must allow a rational resolution of the interactions following full discussion and analysis. These considerations become particularly important when design agents are widely distributed geographically and represent different interests e.g. builder, owner, consultant and government. Under such circumstances the use of Standards for the Exchange of Product Model Data (STEP) is essential.

The extension of the design process to include the design for production activity has the following primary objectives:

- To produce a design which represents an acceptable compromise between the demands of performance and production and, where appropriate, takes into account the needs of overhaul, repair and maintenance.
- To ensure that all design features are compatible with known characteristics of the shipyard facilities.
- To apply the individual design for production principles and procedures insofar as they are relevant to the particular vessel and to the particular shipyard where the vessel is to be built.
- To co-ordinate the inter-relationship between the machinery, electrical and outfitting work with the structural work, in order to create a fully integrated design model.

It is, of course, vital that the design for production effort starts early in the design process. The designer has the greatest influence on the cost of the vessel during the earliest design stages when primary parts, materials and equipment and the basic configuration are being decided. The influence the designer has on cost drops off quite rapidly in the later design stages. It is the ability of modern databases such as object-oriented databases to hold large amounts of data in a format which represents the product model in a manner consistent with production and management processes that ensures accurate representation and thus costing accuracy during the earliest stages of the design process.

Framework: CAD Based Design For Production

This framework is presented as a means of implementing a design for production philosophy using the approach of a product information database. Information can be presented as a design data structure and a production data structure at the same time. Currently, most product information systems utilize object-oriented technology, meaning that information is stored as "objects" in the form of shipbuilding components (i.e. panel, plate, stiffener, bracket, etc.). The properties of sets of components are then used to derive a graphical representation. A discussion of shipbuilding CAD/CAM systems can be found in Ross's review of modern ship design systems [17], and comparative evaluation of commercial CAD/CAM systems [18]. The general conceptual framework is illustrated in Figure 2.

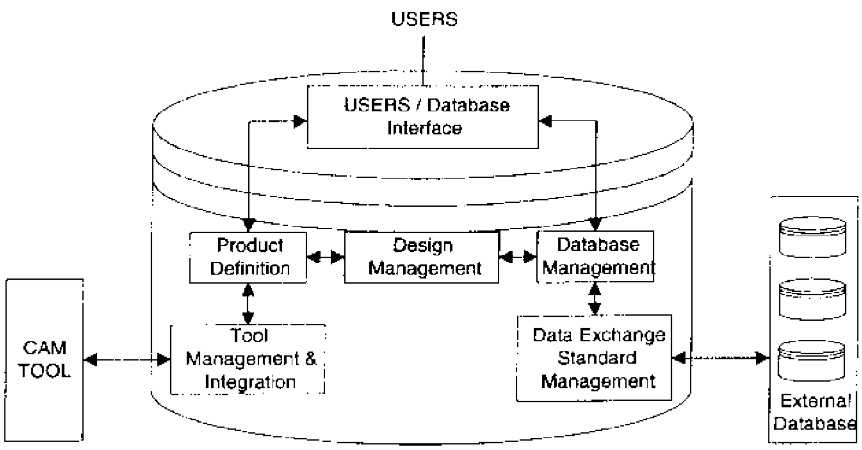

Figure 2. A CAD Framework

The product information database combines the CAD tools and product management system. The structure and configuration of the proposed CAD based generic framework are: 1. User database interface module - the CAD system should be developed to support the user in accessing data stored in the database. The objective is to give the designers from different disciplines appropriate access to the information. This module should maximize the communication between designers and the product information database. 2. Product definition, design management, and database management – the main responsibility for this series of modules is to get information from the user interface for data manipulation. The module acts as an interface among product definition, database, and CAD tool. 3. Computer aided manufacturing – this part contributes to tool management and integration. 4. Data exchange standard management - because of the variety of product models in various shipyards, the product information is shared in the shipyard and with close subcontractors. Currently, unless developed from the same platform, there is no simple way to share product information. To be able to fully utilize the integration of design and production, data exchange standard management is needed. Its primary task is to provide a means of exchanging design information between product data systems.

For product data models, using international standards to better couple PDM systems with the CAD systems is one requirement for future product data models [18].

A necessary of requirement of CAD systems utilizing the design for production philosophy in a modern ship design system is the ability to aide the designer in utilizing preferred production approaches. Additionally, data exchange standard management is necessary for implementing a totally integrated system. Research reviews show that the product information database plays a significant role in ship design, especially concerning data sharing between different design disciplines. It is now viewed as a critical element for productive shipbuilding information development. Some of the benefits include, easy generation, maintenance, and updating of design information, reduction in the amount of error and rework in both design and production, encouraging the consideration of crucial production factors during earlier stages in design, and assisting coordination with production automation, such as NC cutting and robotic welding.

In the current market, commercial shipbuilding is critical to industry survival. Therefore, the ability to handle a larger variety of products is necessary. The philosophy of mass customization is a potential solution. Mass customization is the mass production of individually customized goods and services [19]. It obtains economics comparable to mass production but also provides the flexibility needed for individual customers [20]. According to Pine, one of the design principles for effective mass customization is a product that is comprised of standard, independent modules that can be assembled to form different final products. Ship blocks should have the character of modular design and common platform in order for the mass customization concept to be thoroughly executed in shipbuilding. The common platform concept must extend to both higher and lower levels of assembly. In shipbuilding, the common platform is initially established at the block level (Figure 3). This is called a common generic block. To date, this "type" block concept is implemented by a shipyard based on empirical or experience based analysis. CAD systems have not been able to aid the designer in identifying when a design conforms to the chosen common generic blocks.

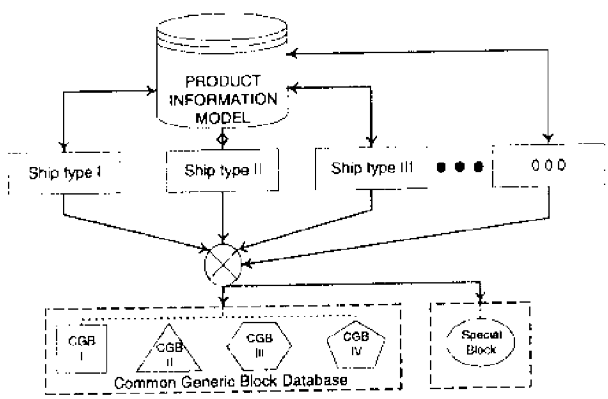

Figure 3. Common Generic Block Database

The common generic block database will have to have a direct interface with the CAD system shown in Figure 2. This external database must be queried by the design definition module to indicate to the designer how well the developing design fits with current production practice and preferences, as identified by the existing common generic block database.

Design Using The Common Generic Block Concept

Another related issue is how to bring information about how well the design conforms to the common generic blocks to the designer earlier in the design process. Figure 4 shows the arrangement of ship design information flow. When developing the approximate ship definition, the design team performs functional design calculations for optimizing ship system performance. Transition design takes the results of these functional designs, and organizes design components based on a block breakdown definition.

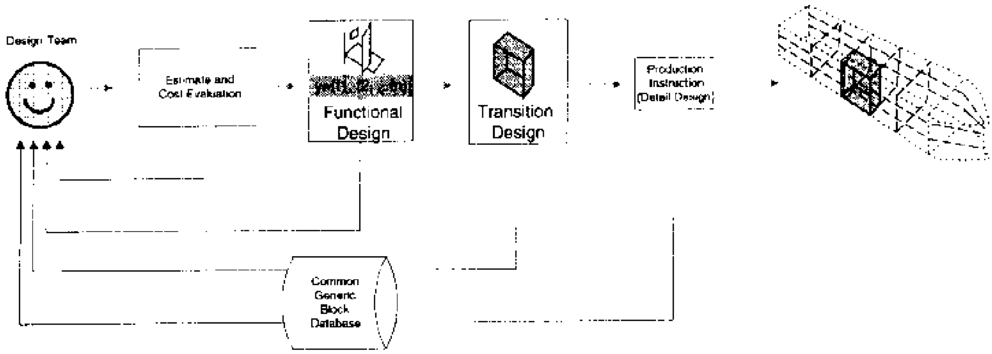

Figure 4. Information Feedback from Transition Design and Production Instructions

In order to utilize the design for production philosophy, early transition design results must be compared with the common generic block database to develop an understanding of how well the progressing design conforms to production preferences. Early in the design, information from the end-product level (transition design) is limited or non-existent in current CAD systems. The interacting effects among design components that form the high-level subassembly are incorporated only through experience. The feedback of information from high-level subassembly is lacking. CAD systems in the future must overcome this deficiency.

Furthermore, approaches to remove the empirical nature of common generic block formulation and evaluation must be developed. Two main qualities of a CGB are commonality and utilization of preferred production practice. The CGB needs to be able to be used in different sections of a ship and in different ship designs with minimum modification required. This quality will be examined primarily during final block assembly and the erection processes. In production planning, it is extremely desirable if the CGB can maintain workstation sequencing or minimize rerouting of process lanes as much as possible. The organization of product family analysis will be the key to find commonality. The development of product family analysis for possible common features is a major link in design for mass customization and context coherent integration. The finding is about what are the common features for a group of related products. Additionally, CGB production should reflect current shipyard capability in manufacturing and assembly. Establishment of the CGB categories should represent preferred production practices based on the principles of design for production.

Using a hierarchical structure, a technique is currently being developed using a matrix approach to allow a comparative evaluation between different block designs. The Block Complexity Matrix is comprised of three matrices, the S matrix, C matrix, and J matrix. The hierarchical concept is linked with accumulative assembly. The S matrix shows the degree of stage assembly difficulty. The J matrix represents the joining difficulty of each of the C matrix components. The measurement approach isolates the stage and sequencing effect on the product, while allowing the integration of interaction effects among design components.

Block complexity matrix = Σ(Block difficulty of attribute q) = S•C•J
where

$$S = \begin{bmatrix} s_1 & s_2 & . & s_m \end{bmatrix} \begin{bmatrix} c_{11} & c_{12} & . & c_{1n} \\ c_{21} & c_{22} & . & c_{2n} \\ . & . & . & . \\ c_{m1} & c_{m2} & . & c_{mn} \end{bmatrix} \begin{bmatrix} j_{11} & j_{12} & . & j_{1q} \\ j_{21} & j_{22} & . & j_{2q} \\ . & . & . & . \\ j_{n1} & j_{n2} & . & j_{nq} \end{bmatrix}$$

SC

Block difficulty

$S =$ a row matrix of the degree of stage assembly difficulty where s_m is a degree of difficult of stage m (ordered from start to finish)

$C =$ a matrix representing block components. c_{mn} identifies individual component n at stage m. The components are identified based on CGB theoretical definition.

$J =$ n x q matrix shows the sum of joining difficulty with q attributes. j_{nq} is a sum of joining difficulty of component n with attribute q

The result should permit identification for each block that reflects production difficulty of that particular block. Therefore, the ongoing design can be compared with common generic block type X to establish their affinities; the block design may be within the common generic block category X, close to common generic block category X, or not compatible with common generic block category X. Designs that are not compatible with any of the common generic blocks of a shipyard may be inappropriate for production by that shipyard. The comparative tools for testing product compatibility in transition design are not available at this time, but are under development and will be presented in the future.

Conclusions

In this paper, a product model for design for production is illustrated, with the emphasis on tool management and data exchange standard management modules. We proposed a shipyard specific CGB database, based on the mass customization principle, to address the increasing demands in commercial ship production. One of the future research areas is to develop techniques to rationally rather than empirically formulate and evaluate CGBs. The CGB, as presented here, acts as a modular design component and common platform. The CGB database is linked to CAD system as an external database. Feedback to the design team during transition design and work instruction design is required to tell how well the design fits the current CGBs. It is proposed that the Block Complexity Matrix, following further development, will provide a methodology for achieving this feedback loop.

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Detailed and Production Design

INTEGRATION OF IT SYSTEMS IN SHIPBUILDING

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And
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Abstract

In shipbuilding today the requirements for short delivery time and reduced cycle are under close scrutiny. A vital part of meeting these requirements is having IT-systems supporting the different business processes involved. Since concurrent engineering is one of the characteristics of shipbuilding, it is also very important to have good integration between the different IT-systems in the process. This paper discusses some different principles for system integration, the relation to shipbuilding business processes and also gives an example of an ongoing integration project.

Process – information flow

The price competition in the shipbuilding industry is traditionally strong and is possibly even getting stronger during the last years. To keep the market position and gain new contracts every shipyard is working hard to become more productive and cutting down any possible overhead. To achieve these goals short delivery time and reduced cycle time is a very important factor.

Shorter delivery time and reduced cycle time is closely connected to the business processes involved in handling a ship project. The main phases are:

- *Basic design*
- *Detailed design*
- *Material Definition (Project or Standard Materials)*
- *Procurement (Procurement Planning, Enquiries, Purchase Orders, Expediting)*
- *Production planning (From initial plan to work orders)*
- *Production (own fabrication and assembly)*
- *Delivery to customer*

Besides the phases mentioned here there are other phases involved in a shipbuilding project but these will not be handled in this paper as the main focus is for the phases involved in engineering, procurement and production.

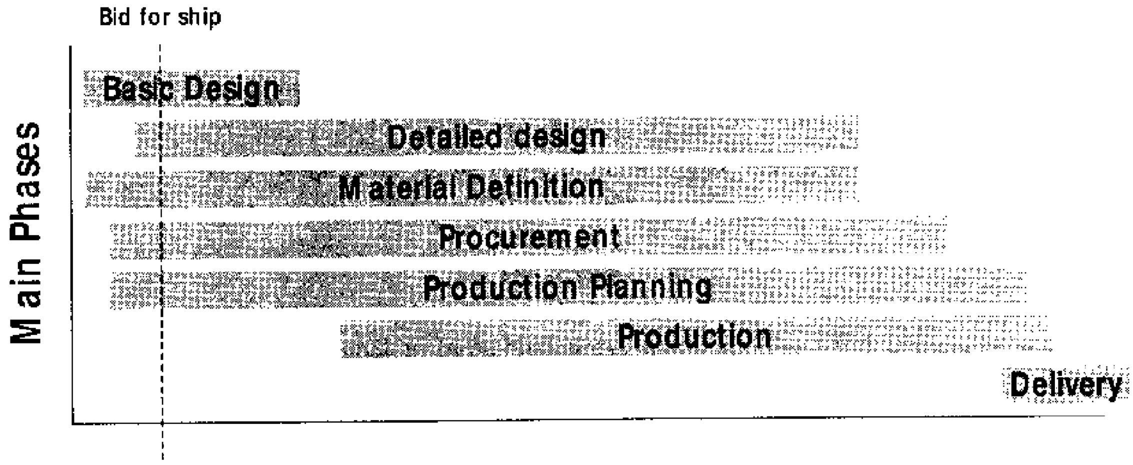

Figure 1. Main processes in shipbuilding.

In figure 1 the seven main processes are illustrated and as it can be seen there is a great deal of overlapping of the processes, i.e. the problems and issues with concurrent engineering have a very high focus in a shipbuilding project.

To handle these issues it is therefore very important to have a good organisation and very good tools supporting the business processes. One of the tools needed is the IT system. The most successful way forward includes good IT systems support as well as good business processes. Therefore the architecture and functionality of the IT systems should go hand-in-hand with the business processes and information flow both within the different organisational units and as interaction between them.

In the following chapters, the seven main processes, the information flow and key issues for good IT support will be described.

Basic design

The basic design is performed in a very early stage and for some parts even before the final contract with the ship owner has been signed. In this phase the main geometry is defined and even some of the key outfitting components are defined. At the same time negotiations with potential suppliers will start to be able to give final price offer for the ship.

A lot of departments are involved in this process; Design, Procurement, Planning, Finance and in some cases as Production and external parties could well be involved too.

In this process a lot of valuable information is collected and will really be the basis for the final offer and also the start up of the further project. Therefore it is very important that within the different departments there are good IT systems where this vital information can be stored and handled. Furthermore it is important that the other departments have access to this information and can use this for their part of the job.

The identification and definition of the main equipment can be used as an example of this. These will as a first step be defined in the design department. The purchase department will based on this and the initial plan from planning create enquiries to potential suppliers asking for prices, delivery terms and deadlines. The suppliers will respond with offers that should be registered and compared and final selection should be made.

Based on this information flow it is therefore important that Design, Planning and Purchase in this phase works on the same core data and the IT systems support this procedure of working.

Detailed design

Some parts of the detailed design will also begin in the bidding phase as a basis for the final offer for the ship. After getting the contract the detailed design will be continued and will reuse all the information collected and defined from the earlier phases. Therefore both the design system and the administrative systems should be able to directly reuse this information and gradually refine the information as well as adding new information.

One characteristic is that from the beginning of a project very little information is known and during the life cycle of the project more and more information becomes available. This also applies to each individual material or part, see figure 2.

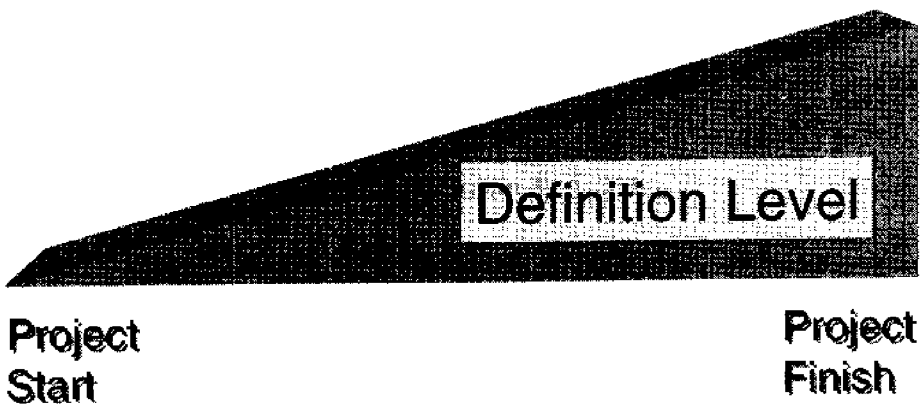

Figure 2. Project life cycle.

In the detailed design phase the complete modelling of the ship is performed and the assembly structure is defined according to the building strategy made in the initial planning phase. Much information for the project in this phase is generated for Material Definition, Procurement, Planning and Production and it is therefore vital that the IT systems support this process and all systems use the same core data. If on the other hand the systems are stand-alone systems there has to be a lot of re-typing of data with the risk of making errors and this clearly requires more resources in all departments.

As discussed before a ship project is a concurrent process and therefore changes in design happen all the time. Having good IT systems the consequences of changes can much more easily be foreseen and actions can be taken to minimise the problems.

Material Definition

For the strategic material needed for a project only a very small part can be considered as ordinary stock material and reordered based on regular consumption. Most of the material is defined specifically for each individual project although they might be standard materials. The material definition are performed as a part of the engineering process and concurrently when building up the part lists for the Assembly Structure.

When the engineering process is performed as a concurrent process it is not possible to complete the material definition and material requirements before the purchase process can be initiated. By reason of this it is important to focus on the right material and quantity rather than focusing on trying to bulk the material requirement which most likely will change at a later stage due to changes in plan and/or design.

The Material Definition phase mainly involves persons from design but also from purchasing department. As all materials defined should go through the purchasing department for enquiries, purchase orders etc. it is important that the IT systems are integrated, i.e. all definitions made by design will be available for Purchase without having to retype the information.

Procurement

For the procurement process there are some characteristics for handling a shipbuilding project:

- *Need for early purchasing of "key" items*
- *Information required is created iteratively and final information is often only available after a purchase contract is placed.*
- *The purchasing process is very technically driven and requires teamwork between designers and buyers.*
- *Purchase of material is often made before the final need-date in production is decided.*

The procurement process is dependent on the category of material to purchase.

For project components and standard project material the purchase process is initiated by the designers creating the technical purchase orders. The buyer can then decide to perform an enquiry process.

At a very early stage it is also, in some cases, necessary to do a planning of the procurement for the key items, i.e. based on the key milestones defined in the planning, the need dates of the key items can be identified. Important information for this process is therefore the definition of the key items, the milestone planning and knowledge of lead-times from the Suppliers. All this information is vital to have available for the process.

For other categories of material the purchase process is initiated by dealing with requisitions from designers and by checking the material status.

The overall philosophy is that this process is partly manual performed. The challenge in shipbuilding is not to have highly developed functions for reordering of standard catalogued items but to focus on the critical items. The purchase process is seen as an on-going process that collects the information from all different parts of the design system and the material control system.

In the procurement phase the main input comes from design and it is therefore important that the design system and the purchase order system work on the same core data. Using the same data source can indicate for the design that the materials have been purchased and maybe delivered and changes therefore should be handled in a special way, possibly not being performed unless it is highly required.

Production Planning

The planning of the work is performed as a building strategy defined through the creation of a work breakdown structure. Most planning is performed in steps starting with a rough schedule that is refined during the phase for the basic design and more elaborated on during the detailed design and production design phase. In the final production planning, the work orders for production are produced based on the overall planning, the assembly parts lists generated, and the capacity and materials available at a given time. For this process it is of great importance that a total overview of design status and procurement status is available. Furthermore, the progress back-reporting from production is important to make as realisticly detailed planning as possible.

Production

In the production phase all information collected through planning, design and procurement will be used for the real production. Production needs information like:

- *What to build?*
- *When to build?*
- *Where to build?*
- *How to build?*
- *Availability of materials?*

All this information is input to the production phase either for manufacturing or assembly. The output of information from production on the other hand is just as vital for the process. This is information like progress. exact use of material and other resources, which materials have been used and where etc.

When high productivity is the overall goal it is of great importance that all this information is stored and easily available for other departments in the company. There could for example be a requirement for a change in design but in case production has completed their part it will be very difficult and expensive to make this change. In an integrated IT system the design will have the production progress available and can in that way make a better and easier judgement of the consequences for a design change.

Production will on the other hand also be able to have a better and earlier overview of the design and in that way be able to do better, more detailed production planning even though the final design is not released to production. There will be a clear indication for production of what is going on in the design phases and actions to prevent problems can be taken more easily when having an effective IT System.

Delivery

In the delivery phase all information for design, procurement, production etc. is necessary to perform both the commissioning and delivery of the vessel inventory or assets register (all items included in the vessel including installation information and procurement information).

Collecting this information can be difficult as this information is traditionally stored in many different systems and the question is really: "where is the master?".

Therefore good IT support for this process is very important and an integrated solution will be of great importance in order to do an easier and more consistent job.

Different principles for IT system integration and co-existence

Principles

The integration of IT systems can be done according to a number of technical principles. These principles are varyingly suitable for different cases. The implementation cost, the organisational and supplier dependencies as well as the maintenance and amount of automation will not be the same. The principles can be applied in varying ways and also be combined within one implementation. Four different integration principles will be described. These are the following:

- *File transfer*
- *Process-to-process communication*
- *API*
- *Common database*

File Transfer Principle

The File Transfer principle means that data is exported from one system and imported into another. This is in principle a copy operation and can be considered a release mechanism. The file format can be either a standard or custom data format. It is also possible to generate program files that are to operate on the target system's data rather than data files, examples of which are SQL, Java, system specific scripting etc. A problem with standard formats can be that they normally exist in different versions and levels. This can especially be a problem if the exporting system supports a later version or higher level.

When data is exported, certain criteria are usually applied to the base data in order to select the records or objects to be handled. This means that the selection of data for transfer usually is the responsibility of the exporting system. The selection can be performed in different ways, of which one is to automatically handle transactions. These can be recorded by setting a flag on the system data when changes are made. The flag can later be used as a criterion for transfer and will thereafter be reset when the export has taken place. This is however a mode of operation that is sensitive to lost data, which can occur if a transaction file is never imported into the receiving system due to manual or computer system error. Any following files will not contain the lost transactions, so an inconsistency will occur. It will be difficult to find and re-transfer the lost data. If instead the transfer file each time consists of a total copy of the exporting system's data, the inconsistency will not occur. This method will however mean that large amounts of unnecessary data are transferred each time. Apart from the automatic selection method described above there is also a possibility to manually select the data to be transferred which will make the responsibility for data consistency to lie in manual routines.

Sometimes an in-between processing or manual editing is applied to the file before it is imported to the receiving system. The processing can for instance be a conversion between different file formats, appending data from another source or applying a general calculation onto the data.
When the file is read into the receiving system, a validation process is usually applied, which means that some records or objects might be rejected or imported with a non-valid status. In the worst case the import operation will be interrupted, or the whole file will be rejected. The process to correct the data and re-transfer the rejected records can be done more or less automatic, but most often relies on a human operator to take corrective action.

The file transfer principle can be further automated on both the exporting as well as on the importing systems side. The sending system can for instance write files automatically on regular intervals or when certain events occur in the system. When a file is written, an importing process of the receiving system can be activated by the sending system. There is also a possibility that the receiving system can be polling a certain directory for new files at regular intervals and then import and delete them.

If the sending and receiving systems reside on different platforms or in different locations, there are methods to distribute the data automatically, among these are shared network disks, scripted FTP or email.

File Transfer Principle Conclusion

An advantage of the file transfer principle is that it does not require very much implementation effort, especially on the sending systems side. If standard file formats can be used, there is sometimes no need for any implementation work at all in order to transfer data between two systems.
The major drawbacks are that it is not on-line, importing validation and correction of data can be error-prone and cause a high degree of manual intervention.

Process-to-Process Communication Principle

The Process-to-Process Communication principle means that running programs and processes communicate and transfer data in real time. This requires an agreed application protocol and must normally be based on a common networking principle like TCP/IP.

Process-to-process communication can be made more immediate than file transfer, and can support transactions. By transactions is meant that transfer of data can be directly performed upon data updating events or release operations. The transaction will then require an acknowledgement from the other system before it is successfully terminated. If the other system will not give a correct response, or not respond at all, the transaction will not be carried through and the sending system will know that the data was not correctly transferred. This reveals a drawback with the process-to-process communication principle, where the systems will be dependent on each other for successful operation. The malfunction of one system or a communication disruption will render the other system unusable. There are complex schemes to circumvent this situation. For instance can transactions be buffered and batch updated when the communication has been re-established. This can however cause difficult situations if a buffered transaction will be rejected by the receiving system.

The process-to-process communication can be implemented on different levels of abstraction. High level principles include such methods as object brokers, messaging, application server protocols etc. On a lower level, more direct network programming principles can be used, such as sockets, named pipes, RPC and DCOM.

The protocols and principles involved in process-to-process communication are often applicable on both LAN:s (Local Area Networks) as well as WAN:s (Wide Area Networks). This means that technology like ISDN, Internet and VPN (Virtual Private Networks) can be used for communication between systems in physically distant locations, even in different parts of the world.

Process-to-Process Communication Principle Conclusion

Process-to-Process Communication offers an advanced and highly functional principle for system integration, with the especial characteristic of being able to handle on-line transactions. The main downside is the dependency between systems that is created.

API Principle

The API principle means that a system publishes an Application Programming Interface that can be used by programmers. This can be exploited in different ways and can also be combined with other principles. One way to use the API principle is to write a program that uses both API:s and transfers data between systems by using the API calls when the program is executed. An API could also be used to create a file that is handled according to the file transfer principle, or to transfer data using process-to-process communication.

Sometimes API:s support event handling in the form of event procedures, hooks or user exit mechanisms. In this case a programmer can create code that is activated upon system events which activates a function within the receiving system or transfers data. A problem with event handling is that the programmer must normally have a complete and deep knowledge of the whole API and event machinery of the system. Sometimes events can occur in an unexpected order, or different user interaction alternatives can cause different events even if the operation performed in the system is the same. This is especially important if transactions are involved.

On the technical level API:s often require that the user of the API must compile and link his own programming together with libraries supplied by the system vendor. This can cause problems related to operating system versions, compiler and linker settings etc. The linking procedure must often be re-made when a new version of the system is installed. Changes to the API may also require major re-programming. Most suppliers of systems that include an API for customer use however try to keep the elements of the API as constant as possible, and rather introduce a new interface than changing an existing one.

API Principle Conclusion

The API principle offers a very powerful way integrate systems giving possibilities for a high functionality and degree of customisation. This is however highly dependent on the completeness and level of functionality offered by the API. It is also possible to combine with other principles. Drawbacks of the API principle are that it requires programming and API knowledge, and that it can cause a high level of maintenance if API:s are changed.

Common Database Principle

The Common Database principle means that all involved systems operate on the same database. In this way there will not be any duplication of data. Some entities in this database can be considered private to each system and some entities can be common. The common entities can be made up of a common attribute set which is known to all involved applications, and also some specific attribute sets, which are only handled by their owner application.

Common application logic can be applied to the data by means of stored database procedures and triggers. These can also be used for handling replication within the database.
A further detailing of the requirements for system integration based on the common database principle will be discussed further down in this document.

Common Database Principle Conclusion

A main advantage of the common database principle is that it is not based on data redundancy, which will remove the risk for inconsistencies. A drawback is that all involved systems will be highly dependent on the availability of the database.

Degree of Specialisation

The principles and possibilities for IT system integration can be categorised in different ways, one of which is degree of specialisation.

In the category of **Integration Based on Standards** we find standard file exchange and program formats, like STEP, DXF, IGES, EDIFACT etc. If any of these formats are used, the exporting system does not need to know anything about the system into which the data should later be imported, and vice versa. There are also standard formats that can be used to carry system-specific information, which really do not fall into this category. These are formats like CSV, SQL etc. IT system integration based on standards can provide an effortless and low cost way forward, but often requires manual routines, gives a low functionality and makes adaptation to specific requirements difficult.

The category of **Integration Based on Commercial Products** includes systems having ready made interfaces for market leading vendor products, like materials systems having a ready made interface for a specific financial or planning system. It could also be in form of middleware from a third party supplier. Here we find both file transfers as well as process communication and common database. These integration solutions often provide a high functionality that is well adapted to the specific systems. A drawback could be that customisations and adaptations of the systems to specific customer demands may require involving several system suppliers.

Another category is **Custom Developed Integration,** which includes highly specialised interfaces developed within organisations for internal use. Can be between different bought-in systems using proprietary formats or between own developed and bought-in systems. These could be based on file transfers, API:s, process communication and common database. Custom developed integration provides a high compliance with business process needs, but at a high cost. This is also very sensitive to change, where the system suppliers will not consider any specific customer functionality making a new version of the system.

Organisational Units

Between different companies, like suppliers, subcontractors and partners it is difficult to arrange specialised solutions. This is also affected by the fact that the players in this area change more frequently than within an organisation. In this case one must rely on standardised and relatively low complexity integration. Apart from the technical issues, there are also other difficulties in the area of data standards like naming, entity representation etc. Information flow issues like version handling can also be difficult to manage.

Within a company, the organisational units like departments, project teams and subsidiaries can use more sophisticated and specialised solutions. Systems can be developed and adapted to long run business process advantage. Overall decision-making organs can set own naming standards and define information flow according to processes in the entire company. In this scenario, all degrees of specialisation can be applied where appropriate. There are also examples of large organisations where the above scenario is only valid within subordinate organisational units, but not within the whole organisation as such.

Example of Integration Project

During the last seven years Kockums Computer Systems (KCS) in Sweden and Logimatic (LMC) in Denmark have had a close co-operation, which also includes an integration of the two products, TRIBON (Design System) and MARS (Material- and Production Management System). The MARS system is also a member of the TRIBON product family and then known as "TRIBON Materials". Various interfaces using the principle of "File Transfer" rather than an integration has in this period been implemented. These interfaces have mainly been handling the Material Definition part and to a very small extent also some parts of the assembly structure. The interface has only been a one-way communication.

In spring 1998 KCS and LMC had the opportunity to develop a real integrated solution with the principle of a "Common Database" together with a customer. The project was described, discussed and outlined through a January and February 1998 and based on this the final project was set-up and started medio 1998.

At this point in time the implementation of the solution is being done and the first parts of it has been delivered and made ready for production start. The complete project is scheduled to be finalised in year 2000 but with the main focus on deliveries medio 1999.

The integration concept

The concept for the integrated solution is to have a common database for engineering and production including all procurement and logistic information. The base is an ORACLE database to which both systems will read, write and update the data. In addition, it will be possible for the customer to store their own data, see figure 3.

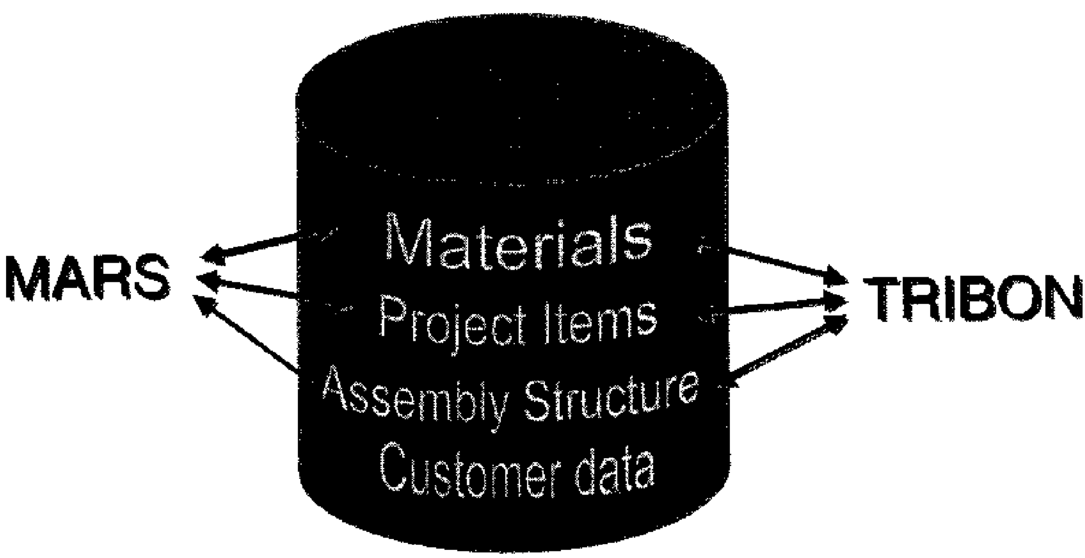

Figure 3. Common data source.

In the common database the data for materials, project components, part lists (assembly structure), project items (unique tagged instances of all used materials/project components) and all production information will be stored. Furthermore, the customer can store data for the Commissioning and Assets Register as all the other data is really the basis for these two sets of data. All other data handled by the Material- and Production Management System will of course also be a part of this common ORACLE database.

Material Definition

The Material Definition in the new concept is possible within both systems. A material can be defined in the design system with all technical attributes, completed in the materials system with all materials attributes and then later on be maintained from both systems with all integrity checks from both systems taken into account. The same principle applies for starting in the materials system and completing the definition in the design system.

There will as described earlier be a possibility to define both project materials and standard stock materials in both systems. However for some stock material it is possible to mark these as not being of interest for the design, e.g. consumables within the shipyard. These materials will not be available in the design system.

Project Items

In the integration project the term **Project Items** has been defined. Project Items is the unique tagged instances of all used materials/project components to be used in building the vessel. Examples of these are machinery, equipment, pipes, cables, cableways and outfitting steel. Hull steel parts are also included in the concept, but the main focus is on the outfitting side, which from a process point of view is more complex. Some items will exist as one instance during the whole life cycle, while others will occur as different entities at different points in time. For instance, a machinery or equipment item will exist from beginning to end, while a system-oriented pipe object will occur during product modelling and the corresponding pipe spools will occur when that part of the model has been finalised and released for production.

In the material and production control systems the type of Project Items that will be purchased as individuals will be referred in the Purchase Orders to make it possible to identify the procurement status for these items. The more model-related items such as piping, ventilation and cableways can be used for forecasting of standard material and project component usage. The production type items such as machinery, equipment, pipe spools, ventilation spools and cableway parts will be members of the common assembly structure and will be the basis for the generation of Work Orders for prefabrication, assembly and installation.

Assembly Structure

All data for the assembly structure will be generated in the design application and stored in the common database. There will also be defined a grouping of project items according to discipline and logistics handling. The Assembly Part Lists in the materials and production control application will then directly read these data from the same source and this will be used for generating Work Orders, Delivery Request Lists and purchase of stock material.

Procurement Data

The procurement data is very important for the entire process both in term of knowing if the items have been purchased but also to know when they are going to be delivered. For the final usage in production the procurement status is a control parameter for knowing if the production of a certain part of the assembly structure can be initiated or changes in production schedule has to be made.

All these information will be available from the Purchase Module in the common database for this project and there will for each project item be shown the current procurement status (technical requested, purchase order send or delivered).

The procurement status will as well have influence on design, e.g. if the status is "purchase order sent" the technical details like material reference cannot be changed without having the procurement department changing the purchase order as well.

All in all this will give more consistent data for all main processes involved in the building of the vessel.

Production Data

Based on the assembly structure the detailed work planning can be performed through the Production Control Module. In this module the Work Orders for the different jobs are created. In the assembly structure the items has been grouped in logical production groups and these can be further refined in the work orders, i.e. having different operations with reference to the items/materials need for each operation.

After completing the manufacturing or assembly the progress is back-reported through functions in the production control module and the production status for each project item will be changed according to this. As a consequence of this it is possible to get a very good overview of the overall progress as well as the progress for individual parts in the process.

The production data and functions are available for all the different item going to be used in the building process, i.e. both outfitting and hull parts.

Customer Data

The customer data in the common database is mainly generated and added by the customer's own applications. It can however also be information generated by various suppliers of either design or materials.

These data will not directly be stored in the data areas for the materials or design system but can be add-ons or additional data belonging to the shipbuilding process. Examples of this can be detailed hour reporting, financial data, commissioning data, other test data etc.

Requirements for Integration By Means of a Common Database

Using a common database as the integration method gives some requirements in the following areas.

Functionality

A common database especially requires functionality in the area of data management. When data is stored in one place, there can be no implicit release mechanism by using e.g. a file transfer. This must then be handled by using status information, release mechanisms and access control. Certain operations should not be possible to perform in one system, when another system has set a certain status. Version handling can also be considered, as organisational units might operate on the same base data, whereas they previously could maintain different versions by controlling the transfer of data between different database instances.

Conventions regarding naming standards and storage formats such as attribute lengths and data types etc. must be agreed between the involved system suppliers. There is also a possibility to use common tables for listing and verification of allowed input values.

Run-time environment

As the common database will play a very central role in the organisation, it is important to plan for using reliable hardware and system software, perhaps also including back-up hardware and emergency plans. The performance of the database server and network will also be quite important since there will be many simultaneous applications and users accessing the common database.

Supplier dependencies

When the common database principle is used with bought-in systems, it is important to get a commitment from the suppliers of these regarding long-term co-operation in product structure, new releases, integration testing etc.

There is usually also a requirement for the different systems to operate as stand-alone when the integration is not used, which gives the requirement that any integration specific functionality should be isolated and not vital for the overall functionality of the system. This is really the most difficult requirement as it often can be in opposition to integration functionality requirements.

Documentation

A further advantage of using a common database is that customers and users can develop applications using direct database access, provided that the database is a commercial easy-access product like a standard relational database. This will give further requirements for documentation of the data model and structures used.

Conclusion

Integration of IT systems in shipbuilding can provide great business advantages in many areas. As new products, standards and techniques evolve, there are many possibilities for advanced functionality. This however requires that the organisation and business processes are adapted, and often needs to be changed. The specific example of using a common database as the foundation for integration can constitute a powerful and highly functional solution.

NEW OBJECT ORIENTED CAD TECHNOLOGY, AND ITS IMPACT ON SHIPBOARD PIPING & POWER PLANT DESIGN

Rick Carell, Rebis Industrial Workgroup Software, Walnut Creek, CA

Introduction

This paper describes current trends in Computer Aided Design CAD tools for shipboard piping and plant design. In particular, we provide an overview of object oriented programming, component technology, and how this technology is implemented to solve specific ship design piping problems.

Competitive pressures to reduce construction schedules and cost have drastically altered shipbuilding methods over the past decade. Traditional practices of building up from the keel have been displaced by a modular approach, where of large vessel sections or blocks are joined together. Computer Aided Design (CAD) tools such a 3-D solid or surface modeling greatly facilitates block design of ships, by improving the accuracy by which individual sections of the vessel fit together. A sample CAD model of a vessel bow section appears in Figure 1 below.

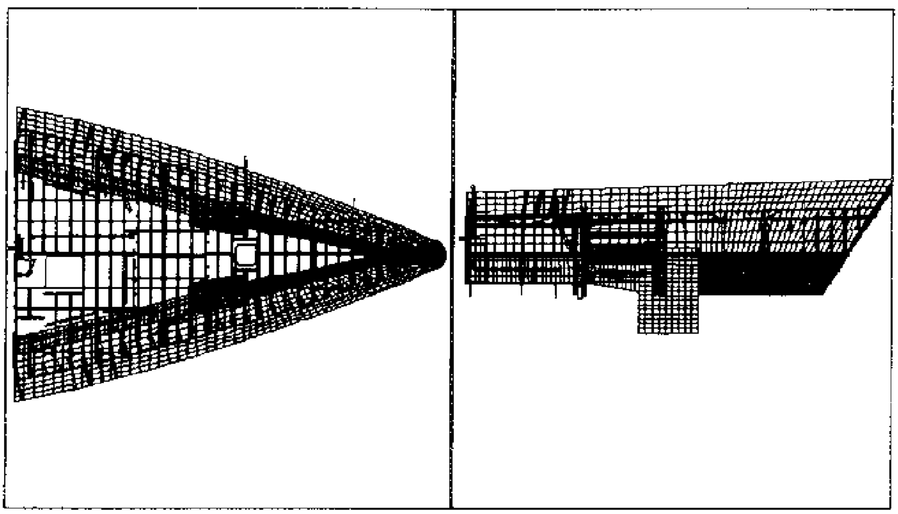

Figure 1

Modular construction enables complex assembly operations to occur in controlled environments and enables ship outfitting to occur concurrently with fabrication of the structure. Outfitting is the installation of parts such as pipes, electric cable tray and equipment in the ship structure. Each ship contains a complete power plant inside the hull, making piping a major cost item. A single VLCC may require over 10,000 pipe supports and hangers.

Pre-Outfitting

Pre-outfitting is the complete or partial assembly of piping and related components in blocks in advance of erection on the dock. Pre-outfitting reduces the need to perform dangerous work in high places and promotes shipbuilding efficiency. The Korean shipbuilders Daewoo and Hyundai, and the US Navy have established themselves as leaders in pre-outfitting techniques. Pre-outfitting is an ideal application for 3-D CAD, and the major yards have developed proprietary systems or adapted elements of commercial CAD systems. High spatial density in the ship block complicates design process, resulting in costly interferences between pipe, HVAC, and the vessel structure.

Component Technology

From a CAD technology standpoint, two major types of functionality are required: Solid and Surface Modeling. ACIS is a widely adopted Solid Modeling kernel. Solid Modeling is highly developed for equipment, piping or duct design; using 3D primitives linked to a database. The ship hull design employs Surface Modeling, where geometric characteristics are entered numerically to generate Bezier surfaces. Many CAD engines have evolved different levels of support for NURBS (Non-Uniform Rational B-Spline) entities to describe complex surfaces.

Numerous commercial and proprietary software for hull design, hydrostatic calculations, accommodation layout, parametric equipment modeling, plate nesting, and NC tool path generation have been developed for shipbuilding CAD/CAM applications; each with it's particular strengths and weaknesses. Many companies have invested heavily to create complex systems which span the full scope of ship design. Large "monolithic" program structures are fragile and difficult to maintain. It is very difficult to isolate specific functions affected by changes in the general environment, say Windows 98 and the underlying CAD engine.

Mirroring the ship design process itself, modular software design or use of component technology is the answer to these problems. The concept goes back to the start of the industrial revolution, with the advent of interchangeable parts in firearms manufacturing. Building code from parts, not from scratch offers a means to speed development cycles and improve software reliability.

In the hardware industry, componentization has long been a driving force for improvement. Chips are placed on boards, which are subsumed into new microprocessors, interconnected with other microprocessors on new boards, etc. Interconnections are driven by standard interfaces such as RS232, SCSI, PCMIA. etc. A lack of similar, practical standards for assembling code has impeded development of component technology in the software industry.

Object Benefits

Object oriented programming or component technology has been discussed in the literature for 20 years as a solution to these problems. On large programs, developers often duplicate efforts writing tools. Even with the best intentions, schedule pressures force programming groups to "hack" out solutions to meet deadlines. Studies show less than 10% of code is re-used on a typical project. Modular design is logical but takes extensive planning and effort. It is important to create a "culture of re-use" to insure the programming team embraces the component method. The main benefits of component technology are:

- Plug & Play
- Interoperability
- Co-existence
- Portability

Plug and play is a concept where you can build to order a complete system out of off the shelf components. Interoperability enables different systems can communicate or exchange data by virtue of standardized interfaces. Seamless integration between Solid and Surface Modeling technologies is difficult to achieve in practice. Users can replace individual components due to environmental or commercial considerations without impacting overall system performance. In the AutoCAD paradigm, in which we operate, the external reference (XREF) function enables us to embed or review complex NURBS topology of the hull as a unit background for interference detection with the piping and equipment. By virtue of standardized DXF or IGES interfaces, we can inter-operate with hull geometry created by other CAD engines.

Component technology improves your ability to co-exist with legacy applications. In the marine piping arena, there are many highly specialized applications that are impractical to port to modern languages. Rebis supports the Isogen interface, a FORTRAN application initially developed in the early 70's that features unique 2D to 3D de-scaling and presentation algorithms.

Portability is a key requirement for any developer to maintain market share. With proper component design, it is possible to support multiple CAD environments. This requires isolation of basic graphic instructions that can be interpreted by different engines, such as AutoCAD or MicroStation.

Development Standards

Development of component standards for software is a critical need. Two competing approaches exist, as shown in Table 1 below.

Table 1. Competing Standards

MicroSoft	Object Management Group
1990 OLE1 – Object linking & embedding	1990 CORBA – Common object request broker
1993 OLE2 / COM - Component object model	
1996 ActiveX- minimization for the web	
1997 DCOM – Distributed COM	1997 OpenDoc – Compound document

The Object Management Group is a consortium of 650 software companies, and provides the leading standard for distributed components. The Corba standard is popular with large Enterprise Requirements Planning ERP systems like SAP or Baan. Microsoft is not a member, and offers a competitive alternative COM. COM is the de-facto standard given it's implementation on every Windows seat sold. COM is in use on over 150 million systems world wide. A growing market of off the shelf COM components is growing rapidly, and estimated to be over $410 million dollars excluding Microsoft.

Rebis has selected the COM standard as the most practical technology available for Windows NT, the preferred environment for our customers. The history of COM lies in object linking and embedding. This is a technique enables you to insert, or "drag and drop" a portion of a spreadsheet in a word processing file creating a compound document. OLE facilities were extended in 1993 and renamed COM. COM eliminated the need to open a separate application window to edit an embedded object in a compound document, accessing it directly. With the advent of the internet, Microsoft introduced ActiveX, or minimalist objects. The overall standard was renamed DCOM in 1997 to reflect "COM on a wire", or extension of the standard in a highly networked environment.

COM Features

COM components which provide services or functionality to other objects are called servers. The object or application using the service is called the client. The main features of the COM standard include.

- Location transparency
- Language independence
- Robust versioning
- Multiple network transports

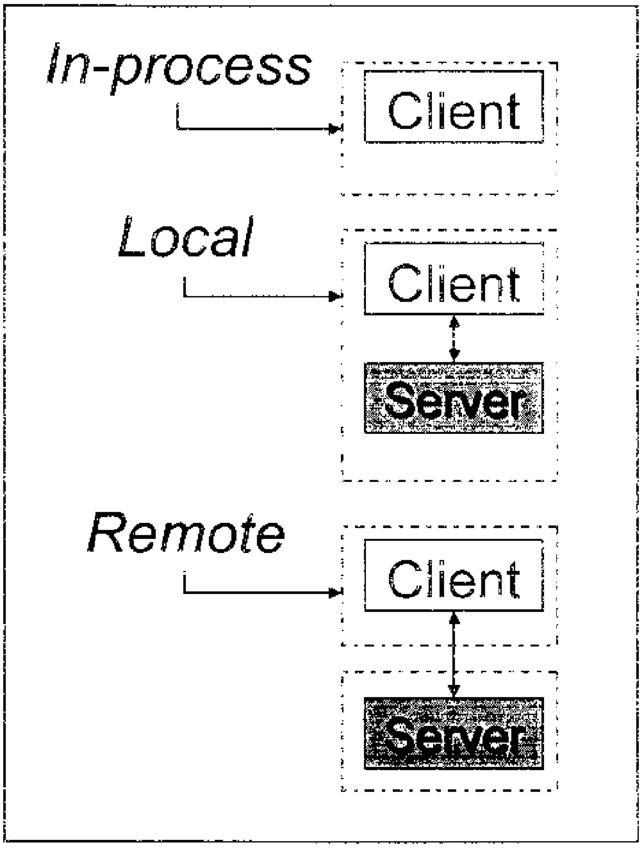

Figure 2 Location Transparency

Location transparency means a COM object does not need to know where it resides. There are three types of client server relationships, In-Process, Local, and Remote as shown in Figure 2. An In-Process component resides inside the client address space. For example, Rebis provides Visual Basic dialog box components that operate within the AutoCAD process which enable the user to enter or review object data. If AutoCAD is terminated, so is the Visual Basic application. A local component resides on the same computer as the client component, but operate independently of each other's address space. An example of local components would be running ODBC calls to an external database, outside of the AutoCAD design application. We are currently using these techniques to develop interfaces from our CAD application to stand alone engineering analysis or calculation programs. Remote components reside elsewhere on the network or Internet. A good example of remote COM components would be interaction of Rebis applications via a PDM or document management application, such as Documentum.

Language independence is a critical requirement for assembling complex systems. COM Objects can be written in many different languages, C++, Visual Basic, etc. Rebis currently uses the Summit Visual Basic scripting language, primarily due to commercial licensing, however this could be replaced with the Microsoft VBA language at a later time. In the past, Rebis applications were developed using AutoLisp, which ran only in conjunction with the AutoCAD engine. In addition to 3 million trained VBA programmers, the ability to embed VBA applications inside AutoCAD, Access, or any other COM compliant applications promotes extension of the system and facilitates integration with in house programs.

Traditional software development practices require you to re-build executables and dependencies each time you add new functions. This is equivalent to re-building the engine of the car just to change tires. Robust versioning enables the developer to add new functionality to a module so that it can support different versions of the same software. Our clients often engage in long term projects where it is impractical to upgrade versions mid stream. COM design principles enable users to modify characteristics of individual objects, say a valve, without recompiling the entire application.

Last, COM supports the broadest range of network architectures. Versions are now available to support UNIX applications, TCP/IP, and the latest HTTP web technologies.

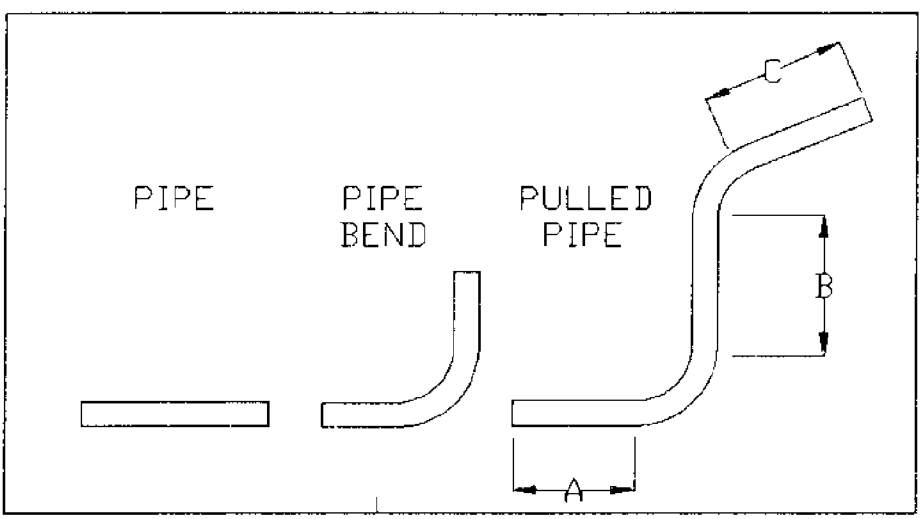

Figure 3 Real World Piping Components

Object Oriented Programming

COM supports object oriented programming techniques. The goal of object oriented programming is to write software the way individuals think in the real world; rather than a procedural language more suited to mimic the logic of a computer. Lets consider the following real world components involved in marine piping design shown in the Figure 3.

Pulled Pipe Object

In order to minimize leakage and insure structural integrity, marine piping minimizes flanged connections and welded joints. This favors selection of multiple pipe bends to change elevation or direction, often at non-orthogonal angles in order to follow the sculptured outline of the hull. These pulled pipe segments are made with multiple bend and turn operations on the bending machine, in the maximum length possible to fit into the vessel block. Each shipyard has various design practices, based on their bending machines, to determine the allowable clamp length = A, fixed block length = C, and minimum straight distance between adjacent bends = B.

In response to customer demand, Rebis has developed a new Pulled Pipe (multi-bend) object to reflect marine design and construction practice. Pulled pipe is treated as an individual object with multiple pipe bends and straight sections. Pulled pipe enables user to route a piping center lines using all the features of alignment, reference points etc. to traverse deck levels, avoid obstructions, and follow vessel curvature. A main benefit of the centerline routing scheme is to simplify calculation of bend angle, which is determined automatically from the polyline vertices.

Object Properties

The object paradigm has been around for many years, and can result in spirited discussions between programmers on whether the application is fully compliant. The three main characteristics of an object oriented program are:

- Encapsulation
- Inheritance
- Polymorphism

Encapsulation

Encapsulation specifies the code is combined with related data to completely define an object. Objects contain public interfaces through which data can be accessed. An interface is a contract between components to provide a set of related operations called methods. An interface defines expected behavior of the object. Each interface is defined by one or more methods. Interfaces for the real world objects described are shown in Figure 4.

Inheritance

Objects are grouped into classes. In our design strategy, Pipe, Pipe Bends, and Pulled Pipe have many similar characteristics and are members of the same class: General Pipe Components. Inheritance is a means to re-use code effectively, by creating or deriving new objects from others. This is especially useful when an existing class has most of the functionality required; but lacks certain desirable features

All COM objects support the base interface I_Unknown, from which all other interfaces are derived. In the example shown, a Pipe object has a several interfaces, including I_Draw to display the component, I_Orient which governs orientation in the XY plane, I_Speckey, which retrieves data from the specification database, and I_Length, which determines the pipe length from user input.

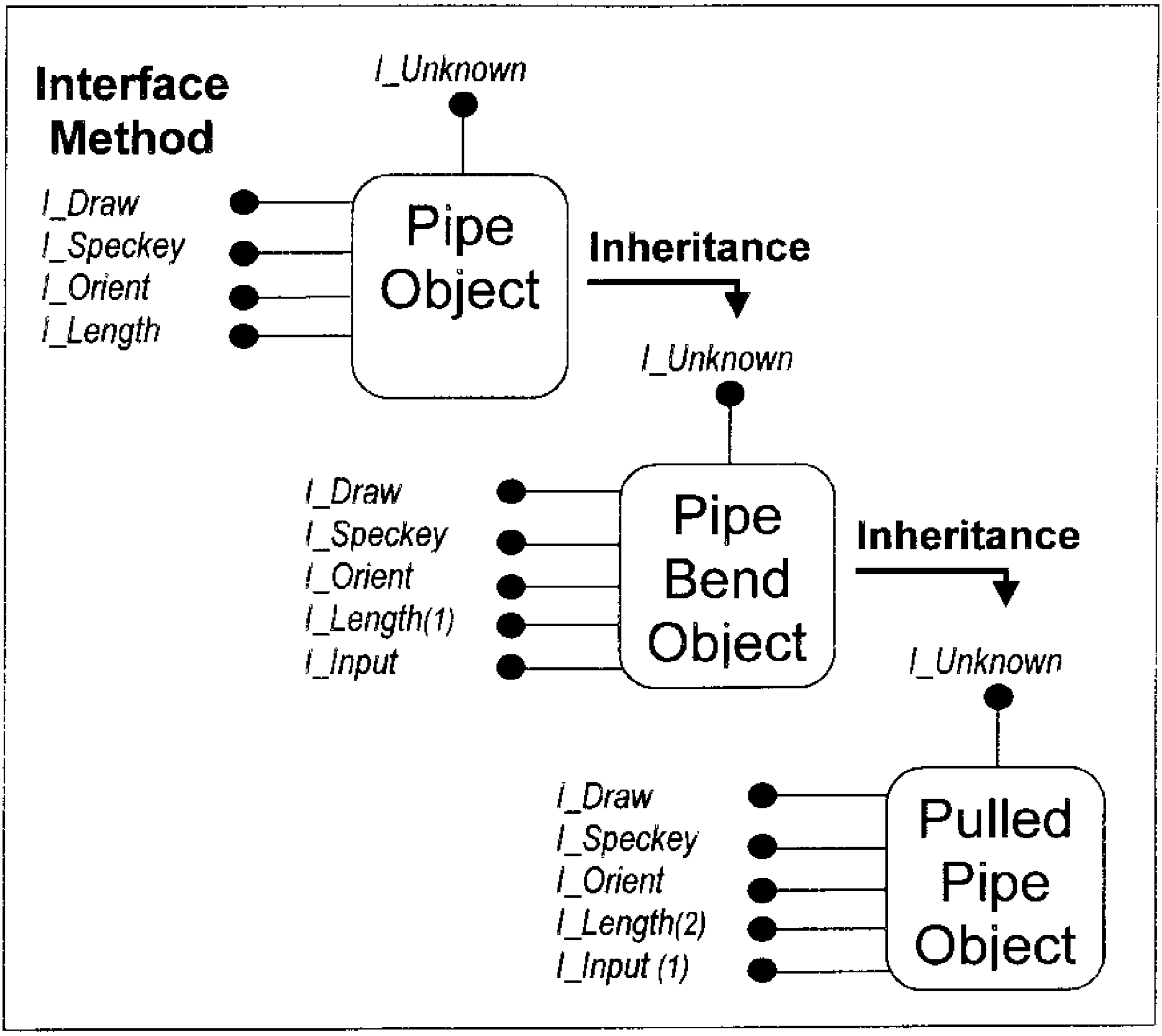

Figure 4 Object Classes and Interfaces

The Pipe Bend is derived from the Pipe object, with identical I_Speckey and I_Orient methods to retrieve non-graphic descriptive attributes and orient the bend in the XY plane. However, the I_Length interface (1) of the Pipe Bend contains custom methods to calculate the two straight A + C legs plus the bend radius. An I_Input method exists to display a Visual Basic dialog box to allow the user to specify bend radius (3R, 5R) value.

The Pulled Pipe object is derived from the Pipe Bend object. It shares identical I_Speckey interfaces with Pipe and Pipe Bend, but has no I_Orient interface because it's orientation is determined from a user specified centerline using the I_Cline interface. The I_Input and I_Length methods are slightly different from Pipe Bend to reflect calculation of multiple straight and bent sections, and enable the user to input a different bend radius at each vertex.

One of the benefits of object oriented design is extensibility beyond the initial specification. To insure manufacturing of the Pulled Pipe piece, we can add a validation interface to check the distances A, B, & C against yard standards.

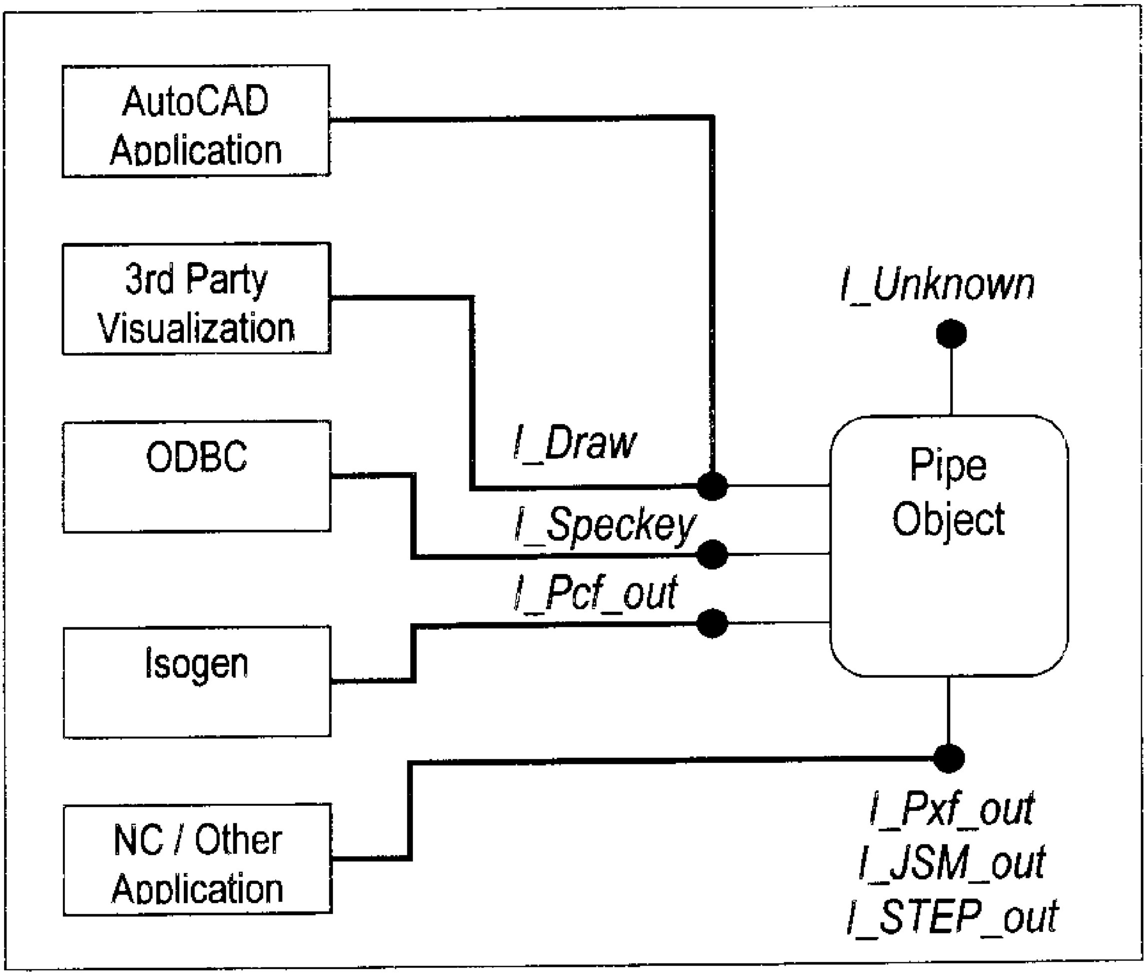

Figure 5 Polymorphic Behavior

Polymorphism

Polymorphism enables programmers to generalize their code, or adapt it to a wide range of applications. The classic example of polymorphism is the Start or Go mechanism. It may be first designed for a Car class, and later extended for an Airplane or Boat class. In the Rebis COM model, certain interfaces such as I_Draw are invoked by various applications such as the AutoCAD piping module as well as the third party walkthrough and visualization programs. Polymorphic behavior of our real world pipe object is shown in Figure 5.

Other visualization packages can be supported with I_Draw, or explicit methods such as I_Pcf_out (ISOGEN format), or I_Jsm_out (PlantSpace format) can be added to the object using the Rebis Class Editor. Non Graphic or descriptive information about part numbers or labor rates can be extracted from an ODBC database using the I_Speckey or related methods. Currently, the company employs a generic file transform utility, I_Pxf_out for exchange of data between design and analysis applications, or supply geometric information to NC or bending machines. As STEP gains popularity, we can quickly extend the object model for a I_STEP_out.

Why Use Components?

In the competitive engineering software industry, vendors must react quickly to changes in system software and rapidly add required functionality. Consider what has happened to the market position of Novell in networking; Netscape in Browsers, Borland in PC database, WordPerfect in text processing, or the phenomenal rise Internet applications to name several examples. Adopting component technology is critical to our overall business strategy for the following reasons:

- Increasing application complexity
- Faster development time
- Easier to de-bug and test
- Reduce integration & maintenance

There has been a tremendous increase in the availability of off the shelf COM software products suitable for use in plant design applications. Studies indicate a $410 million dollar market in COM products outside of Microsoft. Rebis employs many components, such as Crystal Reports for BOM production, DWG unplugged for viewing CAD files, Access or VisualFox for database, Summit for scripting etc. These modules can be replaced for commercial or technical reasons without re-writing the entire application. For example, Access can be replaced with SQL-server for large projects, or visual basic code can be converted to Java script for web compatibility.

Specific features applicable for shipbuilding, such as Pulled Pipe, are important to the end users. However, feature wars will not determine success in today's complex shipbuilding computing environment. Instead, clients are looking for systems which fit into their over all IT infrastructure, and have room to grow. Rebis views it's support of component technology, and the COM architecture, as a key differentiator in the engineering software market.

IMPROVING QUALITY IN THE SHIP MACHINERY OUTFITTING PROJECTS WITH EFFICIENT USE OF GLOBAL COMPUTER NETWORKS

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Abstract

In this paper a systematic approach to ship machinery outfitting projects is described and problems with information quality and security are discussed.

The time available for designing and building a ship is continuously getting shorter. At the same time the machinery systems are getting more complicated. More accurate design is demanded due to prefabrication and smaller space available for the machinery. This development requires systematic and efficient approach to take care that the demanded design quality is achieved and the amount of mistakes and repairing work in construction phase is minimised. A proposal for a solution with standard Windows NT environment and modern 3D engineering software is described and examples of details are given.

The basic problem is to take care that all design is based on latest documents, even when the design work is physically done in several different locations. On the other hand, all information is not needed by each designer in each design office. Too much information makes it difficult to find out which is really important for the design. The solution is to create such an information and archive system, that each designer has access to information he is supposed to need, and the design is as far as possible done in a real time 3D-model visible for all concerned. The new Global engineering network (GEN) is described in the paper. It has following major impacts to the quality of engineering complicated machinery areas:

- Information flow becomes accurate and efficient
- Modifications due to wrong information become obsolete
- System may be physically located in different places and the model is updated via global network
- System takes care that updates to the model can be done only to such objects, which are allowed to be changed by the user concerned
- In the model designer builds a machinery system or a room choosing objects from a component library, which is done for each customer and each project separately. This makes it almost impossible to choose a wrong component or object if the library is carefully built and updated
- Time and material is used efficiently during both design and construction phases

Steps of a ship machinery outfitting project

Ship design work is normally done in several phases. Each design phase is based on previous but is more detailed and accurate than previous. Tools, programs and thus file formats used in different phases are also different. Links between programs are often totally missing or unreliable. Most of the design hours are used in basic design and work shop drawings design. Ship machinery outfitting design is here understood to be the design work which is needed to produce workshop drawings for a shipyard. Scope of work in these projects is normally to produce workshop drawings for production purposes, and sometimes also system diagrams, of a certain area.

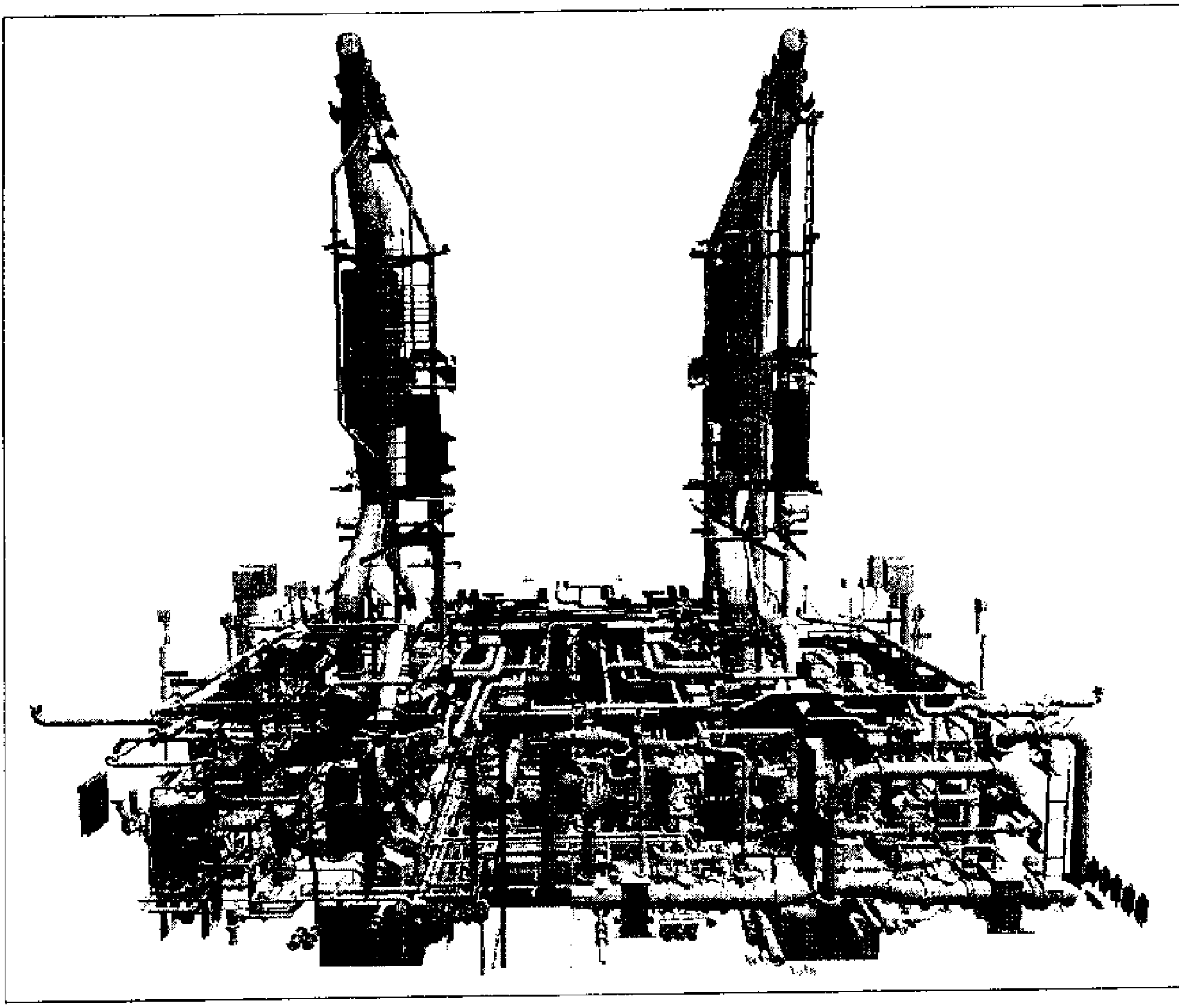


Figure 1. Systems in the engine room and the machinery casings of a supply vessel

Producing workshop drawings proceeds with following main steps:

1. Project organisation is established (Responsibilities, resources etc.)
2. Project archives and work procedures are created
3. Material determined in system diagrams is moved to NUPAS-CADMATIC system by system
4. Standard components are modelled in NUPAS-CADMATIC
5. The model of the hull structures (or a part of it) is updated by the steel design department
6. Preliminary routing diagram is done for piping and air ducts deck by deck
7. Big components and big pipes, pipes with slope, air ducts, lift beams, cable trays, and pipes of expensive material are modelled.
8. Penetrations, openings and possible changes to hull structure are agreed with steel design
9. Sketch of penetration locations is sent to design area neighbours for commenting
10. Pipes and equipment in fixed tanks are modelled
11. Modules are modelled if equipment data is available

12. Small pipes, cable trays etc. are modelled
13. First drawings of prefabricated pipes and modules are delivered
14. First layout drawings are delivered
15. Other drawings and material lists are continuously delivered
16. Model is continuously updated and drawings are revised
17. As built drawings are delivered
18. Project is closed and archives are stored

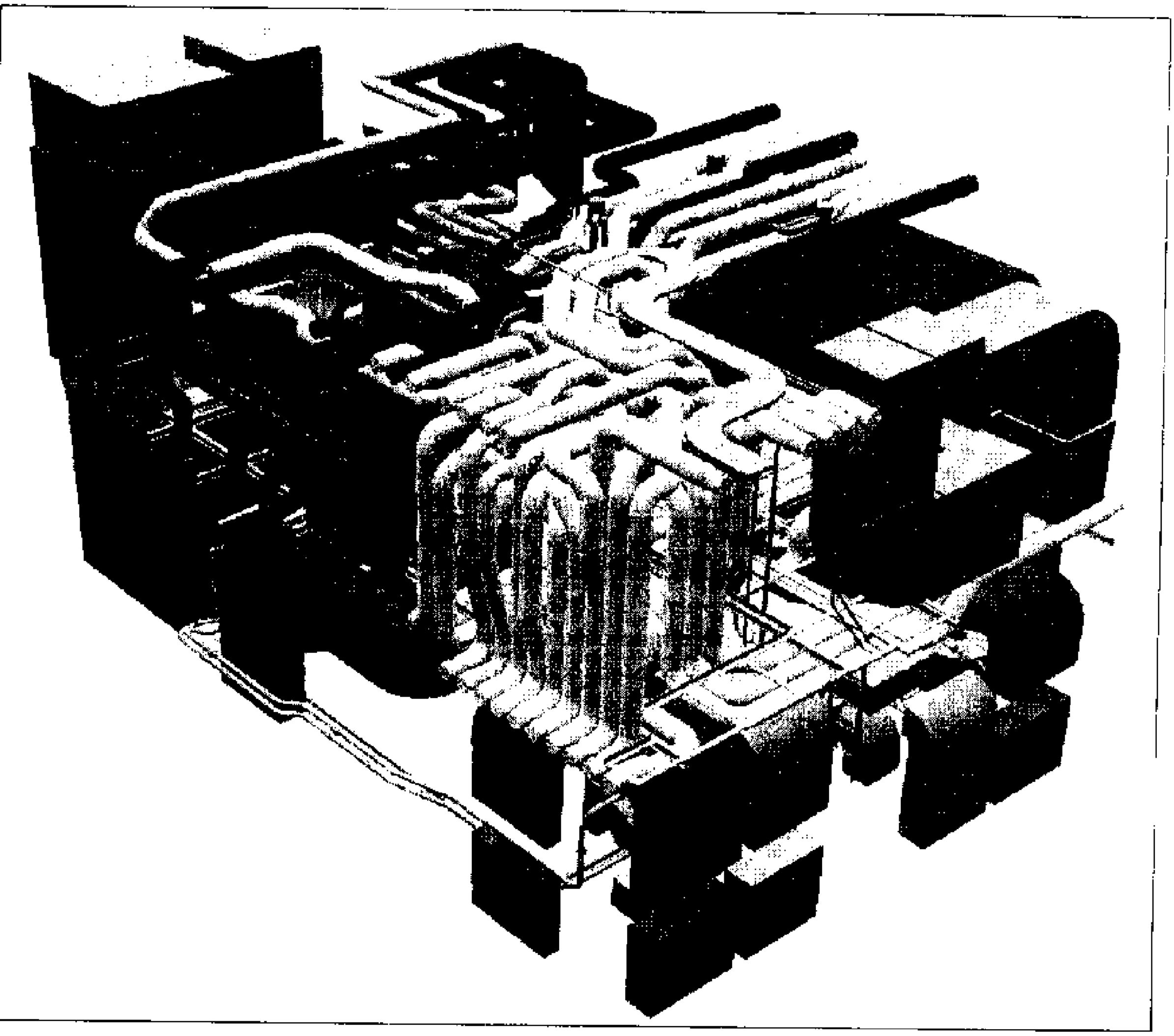


Figure 2. Piping and air ducts in a HVAC room of a cruise ship

This process is not really happening step by step. Almost all phases are still going on at the end of the project. Thus it is clearly seen that data management plays an important role in this kind of work. That is why benefits of electric archives and a 3D model are so evident.

Of course the project has to be complicated enough to make respectively heavy information managing system described here to be worthwhile. Complicity is combination of time available, complexity of the area and of course number of design teams and design offices conducting the work. Due to short design and building times multiple design offices in a same project has become a normal practice. Typical areas for one project are for example engine rooms and HVAC rooms (Fig 1,2), which are probably the most difficult machinery areas. Having several offices from different cultures doing same project simultaneously is a huge challenge for project management and also for individual designers. Each unit has to work strictly as quality instructions require to ensure fluent progress of a project. The design process is here described from the main designers point of view. The main design contractor is responsible for the design quality and is thus also the one who develops and updates the information archives and design procedure.

Information flow

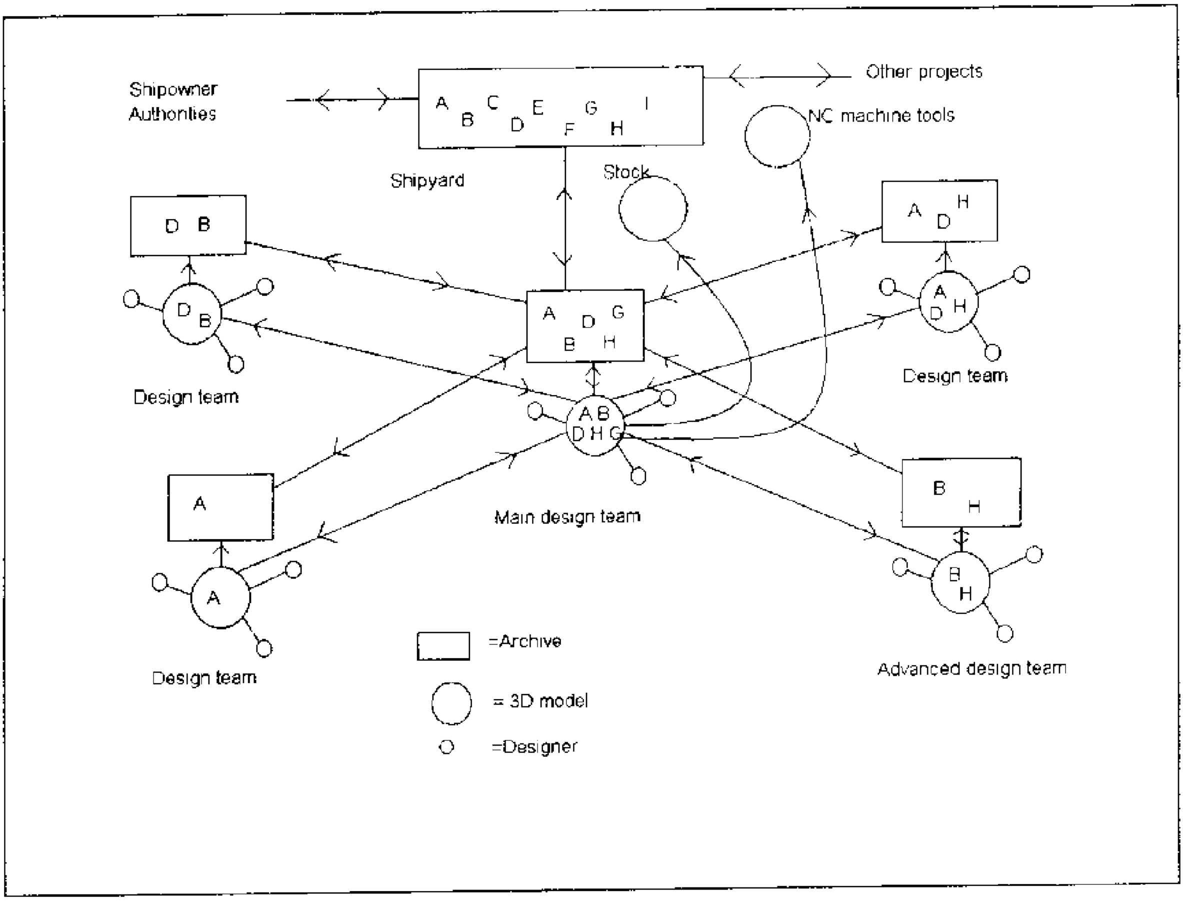


Figure 3. Information flow in a ship machinery outfitting project

Building a ship in a short time requires simultaneous design and construction work. From the designers point of view this means that work has to be done with continuously changing basic information and still drawings and material lists have to be based on latest drawings and diagrams. Also data given to production has to be given as early as possible. This means e.g. that location of the penetrations in bulkheads is required before pipelines are even designed. However all data produced in a project aims to one result: a well done ship built with low costs and delivered in time.

This goal is achieved with rational information flow between each design phase and construction and also between different design disciplines and designers. Fluent information flow makes possible prompt commenting of design and also fast approving and delivery of drawings. It also helps to purchase material at right time with correct information. In a machinery outfitting project input data consists of hull structures, main equipment, yard material standards and rules. After choosing auxiliary equipment component vendors and their drawings become an important data source. All data is connected together by designers. The result of the work is workshop drawings and material lists and at last as built drawings. The material lists can be linked to purchasing and stock material systems of the shipyard. If design work is done in three dimensional environment also a 3D model is produced. Data from model can be straight used for example controlling machine tools. All this requires a huge amount of organising work. Normally the design work is done by several design offices which are often located far from each other. Shipyard is supervising the work and taking care of the ship as a whole. All data transfer between design project and shipyard is routed via main office. Also data from design archive to model is transferred in main office. Exception is modelling components if some of the other offices is capable to do this.

Each design office has a computer network of his own, intranet. These are connected together via global networks like internet or by modems and telephone network. The design philosophy explained here is based on NUPAS-CADMATIC 3D software. All designers of one office are building the same model with NUPAS-CADMATIC. The model is updated by each designer. Each component in the model is owned by some designer and can be modified only by him. However the whole model does not have to be visible to everybody. Each office has their own part of the main model from which updates are sent to main office in which the main model is located. Main office sends updates to the other offices (Fig. 3). The updating procedure sends always all components owned by the sender of update to other users. More practical way will be to send only components which are changed after last updating. All data sent between intranets via public networks should be crypted to make it difficult to disuse it and avoid third part to get access to confidential data.

Global Engineering Network

The basis of working together is communication even if individuals would be on different continents. Purpose of communication is to transfer data and make decisions and agreements. This can be done in meetings, with letters, fax, telephone or with different kinds of computer networks. Choosing the method depends on the type of data and purpose of the contact. If amount of data is big, as is usually if drawings or 3D objects are to be transferred, the most practical way is to send data in electric format. However, the one of the most important tasks in the beginning of a big design project is to make instructions about practises for information delivery, file formats etc. Offers and other official papers are of course to be in paper format because they must be originals and signed and are not updated afterwards. Design data is needed only in electric format because it makes automatic updating possible. If correct file format is used the data can be used straight to design work and thus avoid human mistakes. This should not be a problem, because most of design data is in any case produced with computers. Project management, communication, data transfer, design tools, common data base and document administration are in scope of a development project called GEN (Global Engineering Network). The GEN project is going on in Elomatic. Product data management programs and different kind of distributed data bases are studied. The project works together with an other development project, the GECOS (Global Engineering Co-ordination Support) project of the Helsinki University of Technology. Elomatic is preparing to make a pilot design project based on results of these development projects. The first small step towards a pilot project was taken in a ship machinery outfitting project, in which a main office was in Finland but some NUPAS-CADMATIC 3D modules were modelled in Korea and sent to Finland by e-mail. Same type of co-operation has been also between Elomatic and some Dutch shipyards.

Design archives

Main design office always creates a main archive for a design project. Aim is to collect all project files concerning design to same archive. From this archive documents and files are delivered to archives of other design offices and to the shipyard. If this is done manually, project engineer has a delivery lists in which is shown which data is delivered to which office. All offices have their own archives and own delivery lists of their possible sub-contractors. Other offices send their updated files to main office which updates the project archive with these and takes care of delivering updated files to those who concerned. The aim is to develop this to be an automatic process.

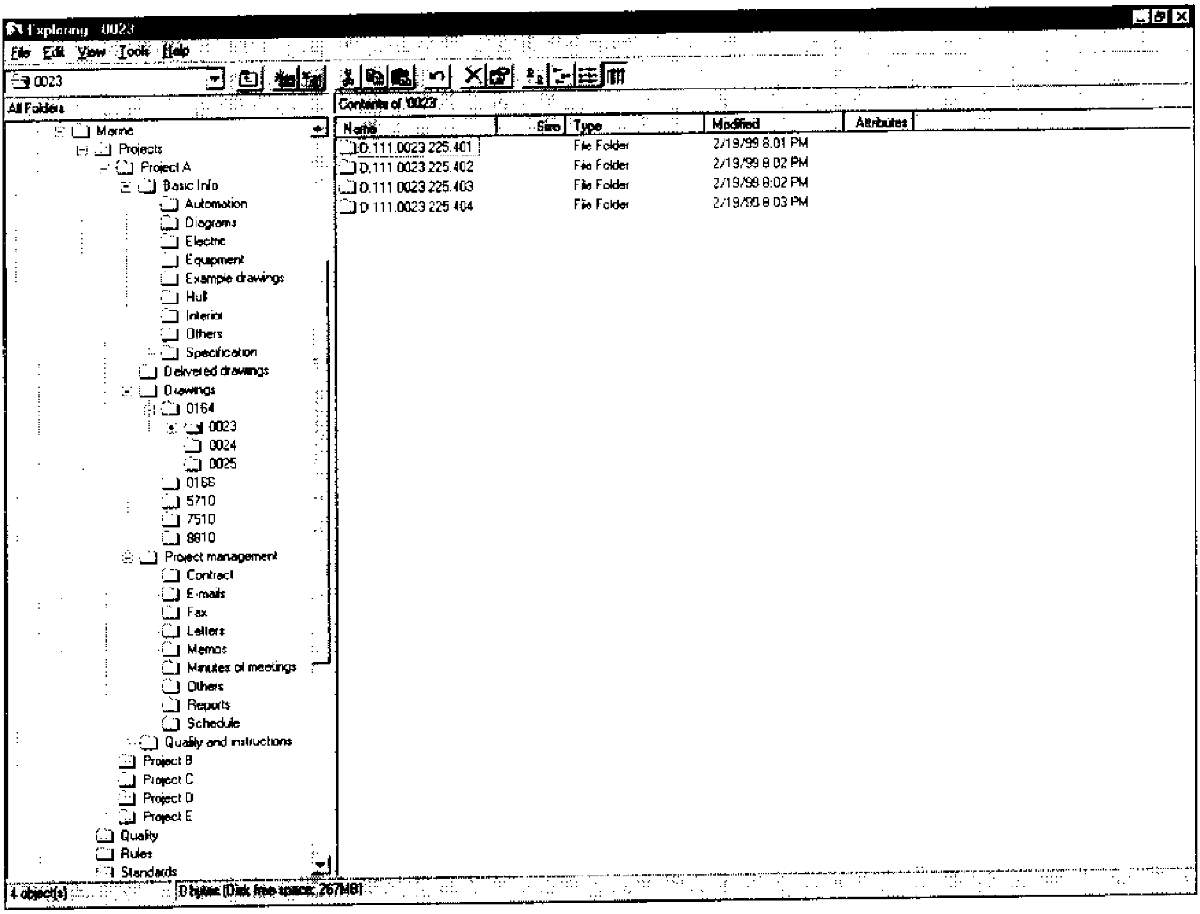


Figure 4. A typical "manual" project archive

There exists already product data management systems which could do this. Instead of delivery to other offices it is possible to allow them access files via internet. In that case risks must be estimated and security has to be specially studied. It must be exactly determined who has access to which files and who has right to update these files. For example if the main office is responsible for all machinery spaces and one of the sub-contractors is only dealing with incinerator, the sub-contractor has not right to get drawings of the main engines. The number of different file formats in one project should be minimised. Especially in international projects file formats should be agreed at early stage in addition to avoid extra problems. File formats in archives and procedure giving names to files should be agreed so that they are suitable for all participants.

In a typical project archive there are different folders for different kind of data. It is to be noted, that while design is done in a 3D environment with NUPAS-CADMATIC, there are not many unfinished files in the archive. All design data is archived in NUPAS-CADMATIC model and drawings are produced from it. These drawings are stored in "Drawings" folder until they are accepted and moved to "Delivered drawings" folder. It is important to take safety copies of both project archive and the model often enough. Safety copying should be automatic to avoid human errors. In figure 4. is shown an example of a project archive. It has main folders for basic info, drawings, project management and quality. Basic info is divided to separate subfolders by discipline. Folder names are chosen to be clear enough to explain what is in them. This makes it less frustrating to follow orders about saving files in the archive. It also helps to avoid problems if part of the personnel in the project changes during work.

3D model

Making a model

The 3D model is built of components which are stored in the library of NUPAS-CADMATIC. NUPAS-CADMATIC has several features which make it useful for this kind of design work. Designers are designing one common model. Each designer can change only components owned by him. The system takes automatically care of standards, routines, production data and some system specific details. So if the main design office takes care of administrating the modelling work, other designers are not capable of making serious errors with standards. Pipes, flanges, bends, fittings and other system specific components are specified by system administrator. Designer has to know the nominal size and system of the pipe only. For example if he is routing a sea water cooling pipe he has to show the route and nominal size of the pipe and the system updates the model with a rubber lined pipe with correct bending radius in bends and correct out diameter. The designer shows location of the flanges and the system cuts the pipe and places a pair of flanges there. Designer does not have to give dimension or system information if routing of a pipe begins from a flange of a modelled equipment. While modelling the equipment it has already been determined what kind of flanges it has and the program does not allow a wrong type of pipe or flange to be connected there. The program allows only correct and compatible components to be used and does not allow wrong pipe class, wall thickness or material to be used. The whole model does not have to be visible for all, which makes size of models in offices other than main office smaller. Work can be divided by systems, spaces or as in most cases by a combination of them.

Walk around

The 3D model is a superior tool for design meetings. NUPAS-CADMATIC has a walk around feature, which means that user can see a view from a virtual camera in the model (Fig. 5). This camera can be moved and rotated in the model and it is possible to determine which systems it shows. Walk around could be developed a tool for distributed design meetings in which designers could see the same view on their on display and have a discussion with phone. This tool is also practical for shipyard's supervisors. Supervisors can make familiar with their own responsibility areas with model. They can also have paper copies of the most interesting views. In the model is stored also non visible data about objects. This data can be asked and viewed during walk around (Fig 8.). The amount of this data can be increased by integrating the model with some data base program. This makes the model and walk around tool to be a powerful tool for maintenance and machinery crew training purposes. This has already been done with NUPAS-CADMATIC and NUPAS-CADMATIC's Maintenance program in some projects.

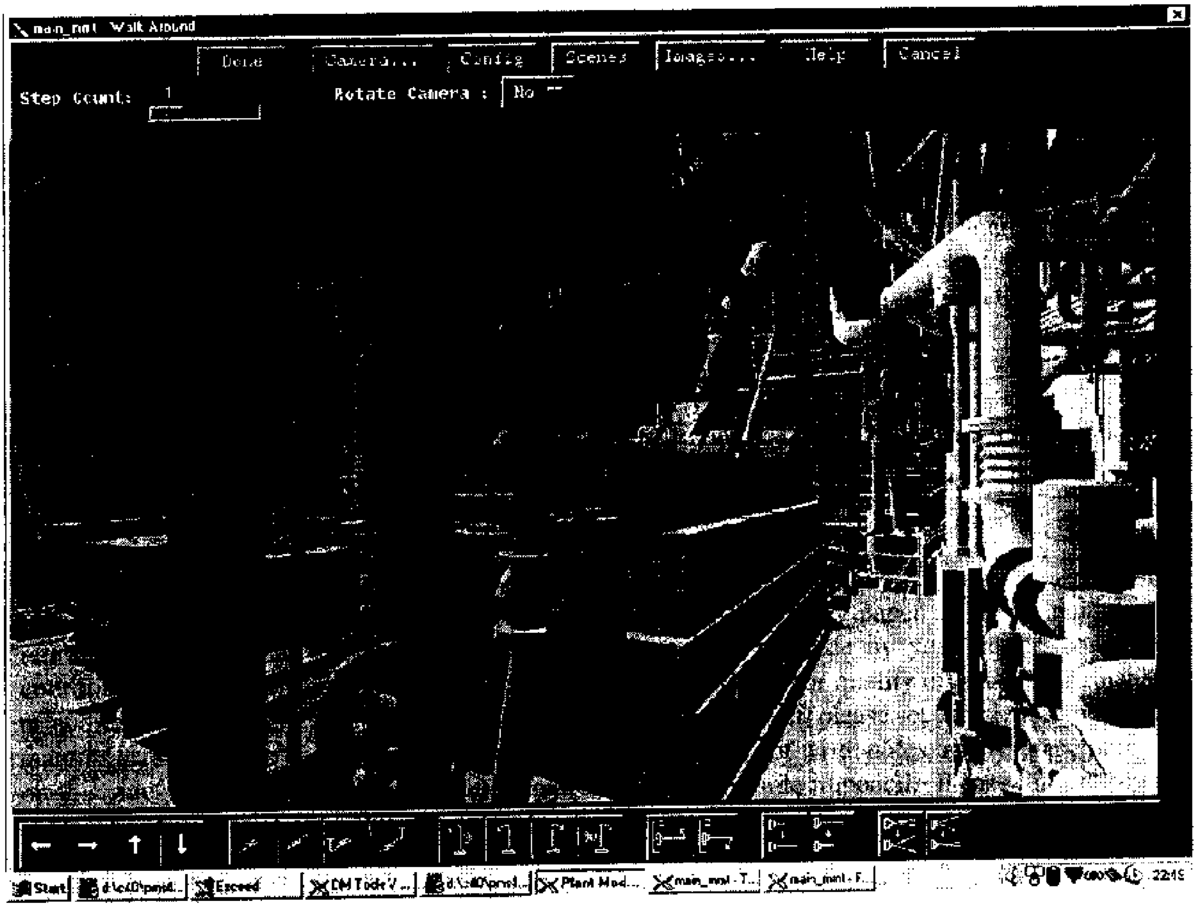


Figure 5. Walk around window of NUPAS-CADMATIC

Paper copies of axonometric views of individual systems are also available. These are especially practical while installing prefabricated pipes and other components.

Material lists

Because the model is built based on system specific objects, it is possible to produce system specific material lists and weight calculations with the model. The user can define which groups, modules or systems are included in listing. Material lists can be linked to shipyards purchasing and stock systems. In that way a real time forecast of needed material can be used as a basis of purchasing.

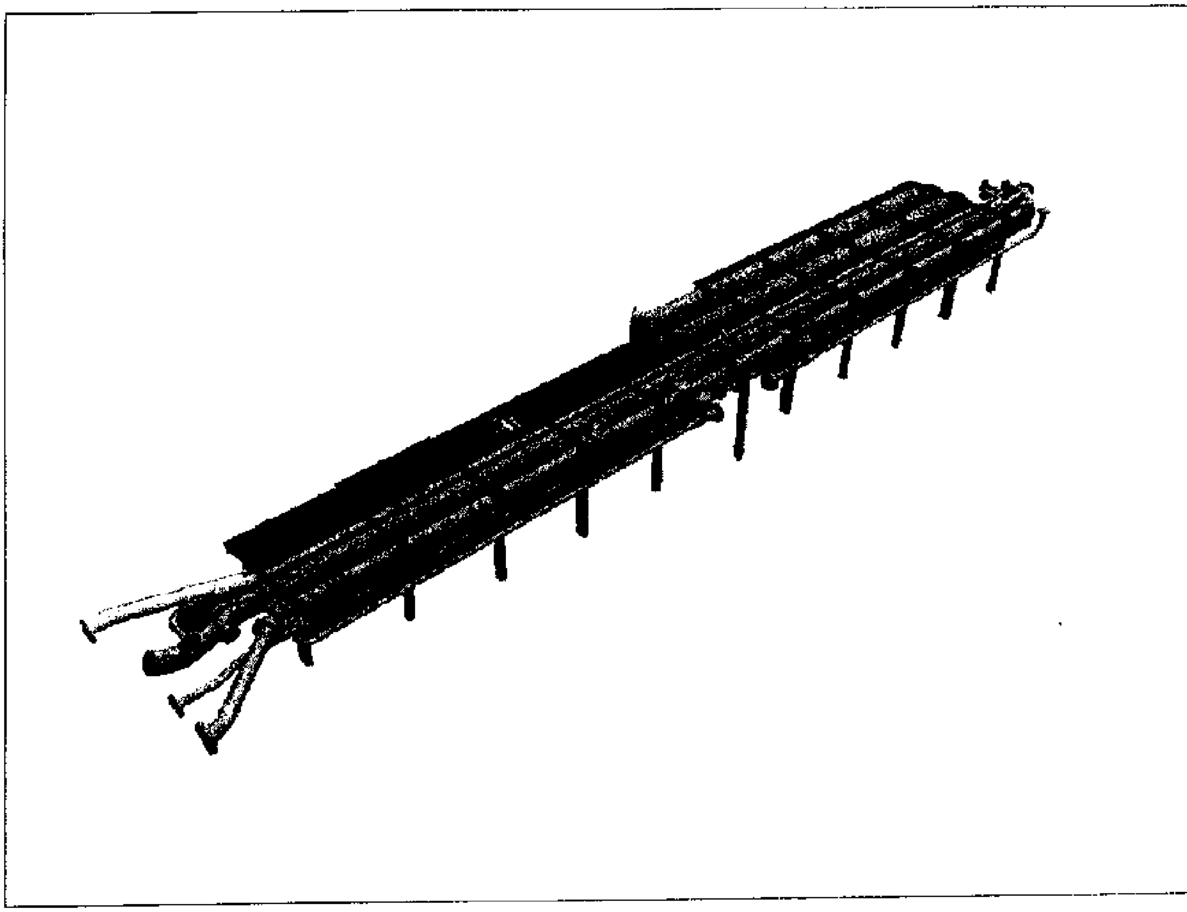


Figure 6. A pipe rack with pipes and a frame

Drawings

NUPAS-CADMATIC is capable of producing all workshop drawings needed. It creates automatically workshop drawings of pipes to be prefabricated. The user can define which systems or user defined modules and groups are shown in a drawing (Fig 6.). He can define sections and projections he wants to show. It has became a practice in Elomatic's ship machinery projects to add a 3D view into drawings. This makes it a lot easier and faster to understand the drawing itself.

Drawings are automatically dimensioned and can be manually edited. Editing work is done with NUPAS-CADMATIC, but finished drawings are easily converted for example into dxf format. This makes it possible for a shipyard to reuse and modify drawings afterwards without NUPAS-CADMATIC or the model (Fig. 7).

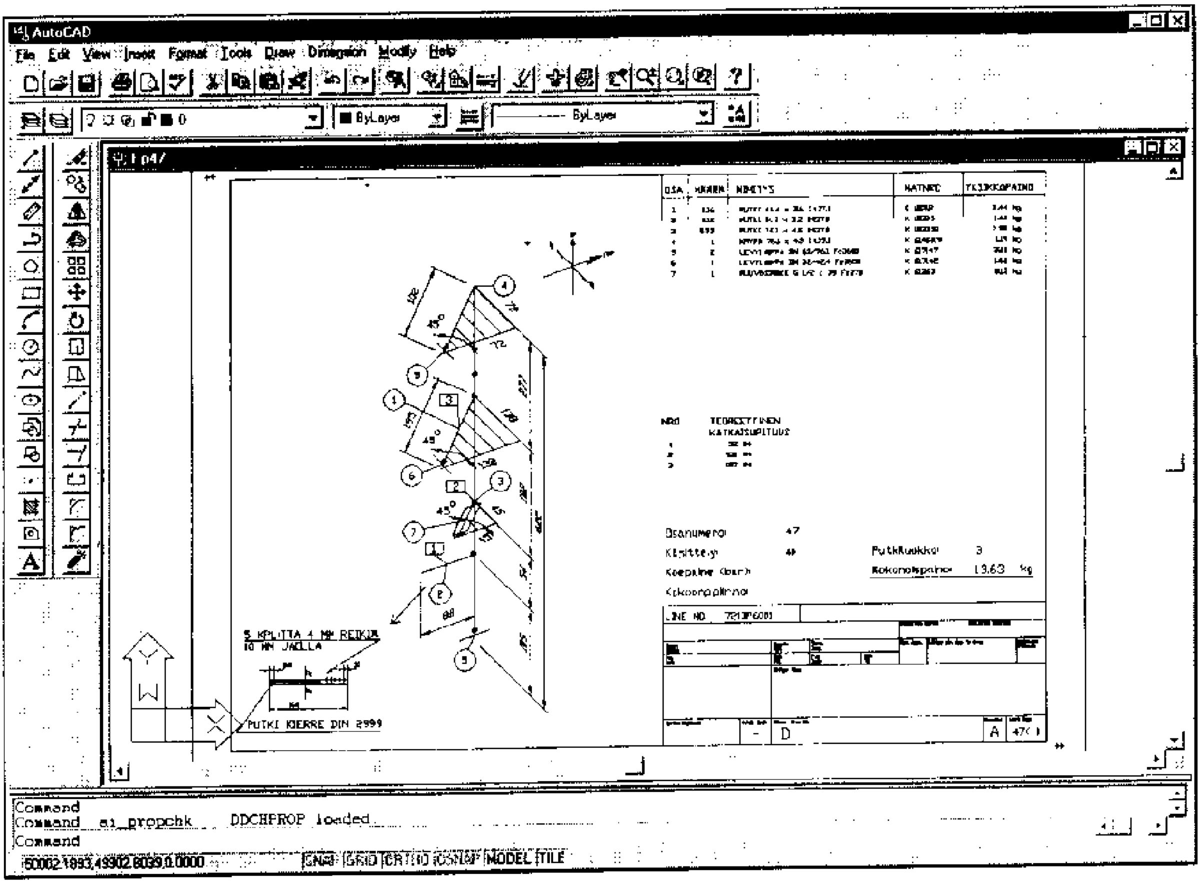


Figure 7. A workshop drawing of a prefabricated pipe created by NUPAS-CADMATIC and imported to Autocad

Tailoring NUPAS-CADMATIC

With NUPAS-CADMATIC's macro language designer can automate part of his work. It is possible to make a macro which creates stairs according to a standard to user defined location. With a macro user can find pipe ends and flanges which are not connected anywhere and take care that there are no missing pipelines or components. With model it is also possible to plan installation of modules and pipe racks and find possible design errors concerning service spaces and heeling routes. Transportation routes and escape routes can be determined as a system and modelled in addition to make space reservation in the model.

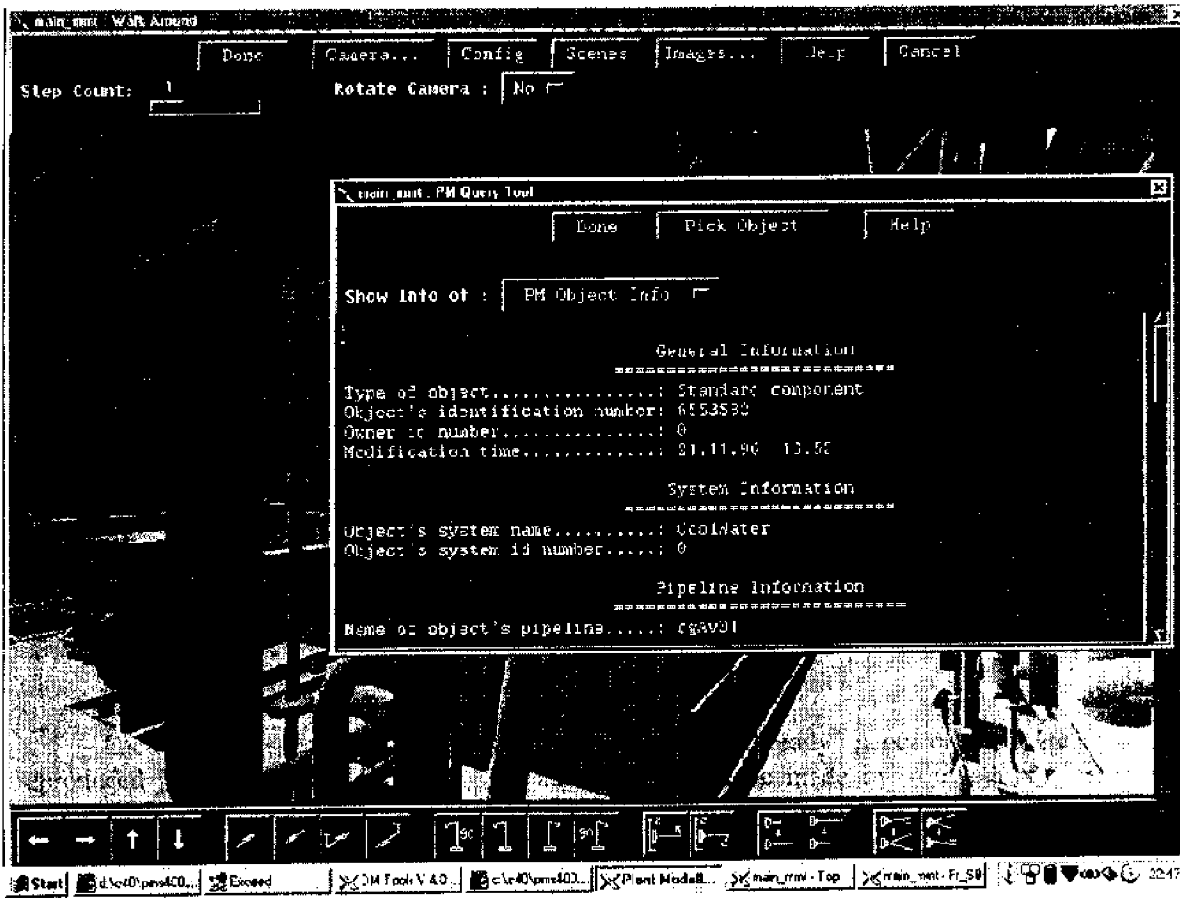


Figure 8. Part query view

Conclusions

A systematic approach to a distributed machinery outfitting project has been developed. Basis of the system are 3D model and global computer networks. More accurate design and information flow is achieved. This saves time, eliminates design errors and makes it easy for a shipyard to increase amount of prefabricated components. A solution for organising a machinery design project with several design offices is only one step towards a virtual ship and integrated design and manufacturing system. If all design work from theoretic project design to details of workshop drawings is collected to one model, it could be possible to find all new real time procedures to design a ship. For example the influence of penetrations and holes made to girders and bulkheads could be analysed immediately. The center of gravity would be known all the time. The crew of the ship could be trained with a virtual ship and their proposals and comments could be taken into consideration in design. Assembly work would be much faster and cheaper if machine tools could get geometry straight from the model. Purchasing material would come more exact if amount of each material and number of each valve type would be read straight from the model. Machinery systems could be simulated and their compliance validated at early stage. Also the construction process might be possible to simulate. Ship models are already in use onboard ships to simulate hydrostatics. More sophisticated models could be used to analyse all important processes of a ship. Complicated failures could be found and fixed faster. In the best case they could be forecasted and prevented. With the Global Engineering Network (GEN) project Elomatic is developing and taking practical steps in getting closer to this idealistic vision.

Preliminary Design

RulesCalc
A System for Integrating Classification Checks with Ship Initial Design Systems

Martin Brooking, Lloyd's Register of Shipping, London, UK
Alistair Stubbs, Lloyd's Register of Shipping, London, UK

Synopsis

This paper describes a new Rules calculation system developed by Lloyd's Register to enable the determination of Classification Requirements using 3 possible interfaces:-

1. A standalone system
2. Part of LR's ShipRight[IS] product
3. Seamless integration within third party design (CAD) systems

The paper examines the business drivers which resulted in the development of the system and shows how RulesCalc provides a significant development in the design and design approval process which will benefit owners, designers, Classification Societies and CAD vendors.

An explanation is also given of how the mechanisms and models used by RulesCalc can be utilised by designers to provide efficient design analysis and other checks earlier in the design cycle than is possible using data exchange based technology (STEP/DXF etc).

The paper also addresses the programming requirements on design system vendors in order to implement RulesCalc within their systems.

Introduction

Many sources of information are used by a Naval Architect during the design of a ship. A typical shipyard has a large resource of previous designs, manuals and standard practices to draw upon.

Whilst they should not be used directly as the sole design control, the Rules and Regulations published by the Classification Societies embody many years of ship building experience and best practice and form an extremely valuable resource for the naval architect.

Currently many of these Rules are accessible only through Rule Books, 3D software systems, limited spreadsheets or legacy systems. This makes the information unnecessarily hard to access and makes their use within the design cycle time consuming.

As a result of this the Classification Rules are often used as a final design check rather than realising their benefits earlier in the design process.

3D Design Systems

The trend in the engineering industry as a whole is moving rapidly towards the use of 3D design based around PDM systems and the principles of concurrent engineering. These advances offer significant benefits to Shipyards in terms of improving quality, accelerating the design process, reducing rework, and hence significantly reducing cost.

Classification societies have followed this trend and produced 3D systems of their own. ShipRight[IS], Nauticus, Safehull etc. These are powerful integrated packages that are able to carry out a number of complex tasks such as FE meshing, ultimate strength and still water bending. In addition they are also able to perform basic Rule checks.

Plan Approval Process

The Rules and Regulations form the principal element of the design assessment process within the Classification Society.

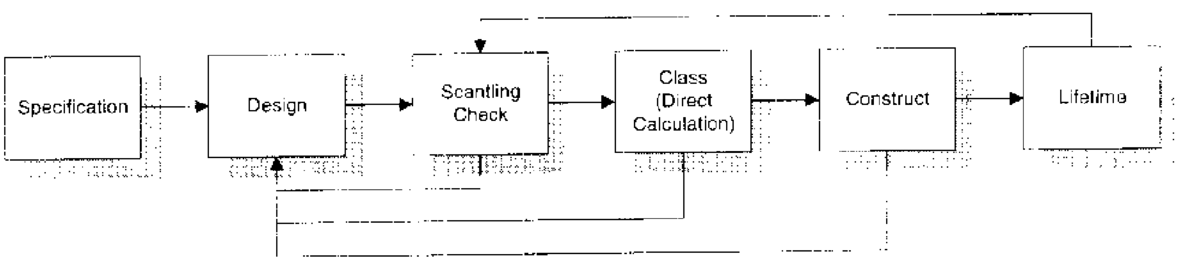
Currently designers provide 2D paper plans of the vessel for approval. Typically not all the plans will be presented at the same time. Rather, collections will be submitted as the design proceeds, often starting with the Midship Section as longitudinal strength is one of the key elements requiring verification.

Using the society's own internal systems the design will be appraised for compliance with:

- any relevant Rules and regulations laid down by the society.
- Regulations set by any interested statutory bodies
- a view to ensuring that the design incorporates current best practice covering design detail, end connections, continuity etc.

The diagram below illustrates the information flow involved in this process.

Figure 1. Design, Construction and Operation



By it's nature this is a time consuming process and it has been proposed that the means to improve the speed of plan appraisal is to incorporate the classification society in the design team. That is to say that the classification society becomes an integral part of the design team, working with the designers as the design evolves.

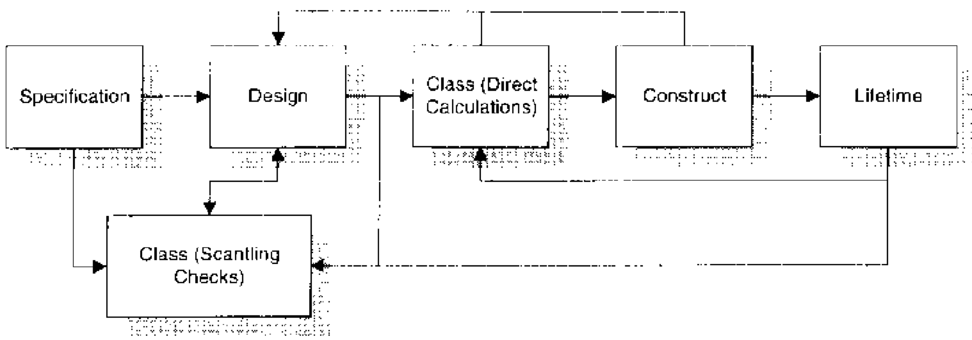
Whilst this is a good idea it is not completely practical:

- Plan approval surveyors typically work on several projects simultaneously.
- Involvement is not required on a continuous basis.
- An element of independence and impartiality must be maintained for classification to remain credible.

However the benefits of incorporating Rule scantling checks within the design process are such that an alternative to integrating a surveyor within the design team is required.

A system must therefore be found that can realise the benefits of integrating the classification checks early within the design cycle.

Figure 2. New process for Design, Construction and Operation



Current technology

There are a number of systems currently available for carrying out basic scantling analysis. However all of these systems have limitations which makes their use less than ideal.

Traditional Bespoke Applications (e.g. LR.PASS)

All major classification societies have developed software systems dedicated to calculating rule requirements for ship structural elements. These started as simple programs running on early mainframe or desk top computers. They have gradually evolved over the years to accommodate PC platforms and the latest operating systems, such as Microsoft Windows. These programs have served the classification societies well, but they have in many cases reached the limit of their development.

The evolution of LR.PASS, for example, has resulted in a diversity of individual applications for which the support and maintenance represents a significant logistic and commercial burden. A major revision of the LR.PASS system would go a long way to solving this problem; but it is now time for a step-change to implement a new type of system which has the flexibility to provide access to Rules checks for third party design systems, as well as reducing the effort required for maintenance.

Spreadsheets

Spreadsheets provide an engineer with an extremely powerful and easy to use tool for performing calculations. The simple calculations required for rule assessment are ideally suited to use in a spreadsheet. The best approach to their use is to develop a number of worksheets each related to a specific part of the Rules, for example a sheet to consider the thickness requirements for weather decks.

This breakdown into a large number of worksheets aids manageability and makes it simpler to identify which sheet to use, however it also results in unnecessary re-entry of basic details such as dimensions, spacing and material properties. It is possible to make systems which automatically transfer some of this data, however this is a slow and incomplete solution.

The development of spreadsheets to support the calculation of the requirements in the Rules and Regulations is attractive to classification societies because of the low cost, maintainability for simple systems and ready availability of staff with the necessary skills, however there are reasons why they are not an ideal solution for the end users.

Experimenting with different solutions is difficult as each solution requires a new spreadsheet. A large number of spreadsheets relating to a project are therefore created making it difficult to find, analyse and report on results.

The use of spreadsheets becomes increasingly difficult where calculations are more complex, e.g. large numbers of interdependencies, solving simultaneous equations or iterative calculations.

Step

STEP technology offers the ability to exchange details of a design between systems and organisations in a neutral format. This can deliver significant benefits to the organisations involved in the construction of a vessel.

To date a number of protocols (APs) have been defined to enable the exchange of information between different systems.

Table 1 : STEP Application Protocols for Shipbuilding Industry

Structures	AP218
Moulded Forms	AP216
Arrangements	AP215
Mechanical Systems	AP226
Piping	AP217
Operation	AP234

This technology has been developed over last 10 years to the point where there is now wide industry support and for the first time it is now becoming possible to transfer information between organisations and systems in a meaningful manner.

A number of key vendors of design and production systems have now implemented STEP capabilities, though at the time of writing the standard of the exchange still requires some development to handle the differences in the implementation/interpretation used by the different systems.

Other projects have built on the basic STEP foundations and now provide protocols and process for the exchange of information. The importance of these less tangible elements must not be underestimated.

The use of the STEP standards and protocols for enabling classification checks is therefore very attractive and Classification Societies have played a major role in the development of the standards. However the use of the standards is not ideal for the basic classification checks which are required early in the design stage.

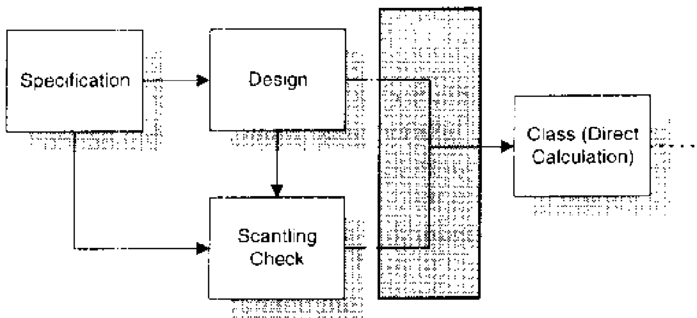
Work on the STEP application protocols has correctly concentrated on the transfer of entire vessel designs or significant parts of a design. For example to enable the transfer of hull form information from a shipyard to a model basin to perform tank testing.

This exchange involves a significant translation element converting, for example, the 3D representation used by the design system at the shipyard into the 3D representation employed by the STEP protocol and back again, to a different system, at the model basin.

Because the intention of STEP has been to enable high level exchange between ship design systems the protocols are based on a 3D geometrical model of the vessel, the amount of detailed data required on a design to begin constructing a 3D model is extensive and this severely limits the applicability of STEP in the early stages of the design/approval process.

STEP does have a significant role to play however in the design process, particularly where more advanced calculations, such as Finite element or fatigue assessment calculations. This is an ideal application for STEP transfer as these types of calculation do require a significant amount of data including hull geometry.

Figure 3. Role of STEP in the Design process



RulesCalc - A new system

All of the systems outlined above have significant drawbacks. An alternative approach which combines many of the benefits and avoids most of the drawbacks has been developed. This approach is described below.

Requirements

In order to allow the designer to get the maximum benefit from the knowledge built into the Rules and Regulations a Rules any system used to perform the calculations must exhibit the following features:

- Enable use early in the design process.
- Support sensitivity studies and assessment of alternative arrangements.
- Show what Rules have been applied to an element of the design.
- List any intermediate results calculated.

The RulesCalc system developed by Lloyd's Register is a system which exhibits all of these features.

Minimum Data Input

In order to be able to start to perform the scantling checks as early in the design cycle as the specification stage it is necessary to be able to execute the calculations with the least amount of data possible.

This requirement is not consistent with the use of a 3D design tool. As discussed above such systems require extensive data input before a meaningful model can be generated. Full geometry information, in particular, is not required in order to be able to calculate the rule requirements. Often the data requirements may be as simple as the location of the centre of a plate, the stiffener spacing on that plate and the function of the plate.

An examination of the formulae in the Rules will reveal that they are fundamentally two dimensional linear equations based on a first principal approach. The use of a 3D design system as an input mechanism for performing basic Rule scantling checks can be inefficient. Far from improving the accessibility of the Rules, the use of a 3D input system can make design verification harder and longer.

The system must enable the designer to quickly enter basic dimensions, material properties, section properties and then start analysing the requirements for structural items.

Rapid Data input

RulesCalc resolves the data input problem, as it can be used to establish the Rule Requirements for a vessel laid down in LR's Rules and Regulations for the Classification of Ships using only the minimum amount of data.

The user interface provides a number of input screens for the vessel data. Once the basic information is entered then analysis can begin.

Figure 4 : Input screen, for Basic Details

	Property	Units	Entered
1	*Length between perpendiculars*	m	270.000
2	*Load Line Length*	m	270.000
3	*Moulded Breadth*	m	45.000
4	*Moulded Depth*	m	2[illegible] (moul
5	*Summer Draught*	m	15.000
6	*Design Draught*	m	17.000
7	*Block Coefficient*		0.750
8	*Load Line Block Coefficient*		0.750
9	*Min. Draught at FP*	m	0.000
10	*Max. Draught at FP*	m	0.000
11	*Min. Draught at AP*	m	0.000
12	*Max. Draught at AP*	m	0.000
13	*Deadweight at Summer Draught*	tonnes	15000.000

Figure 5 : Input screen, for Inner Bottom Plating Requirements

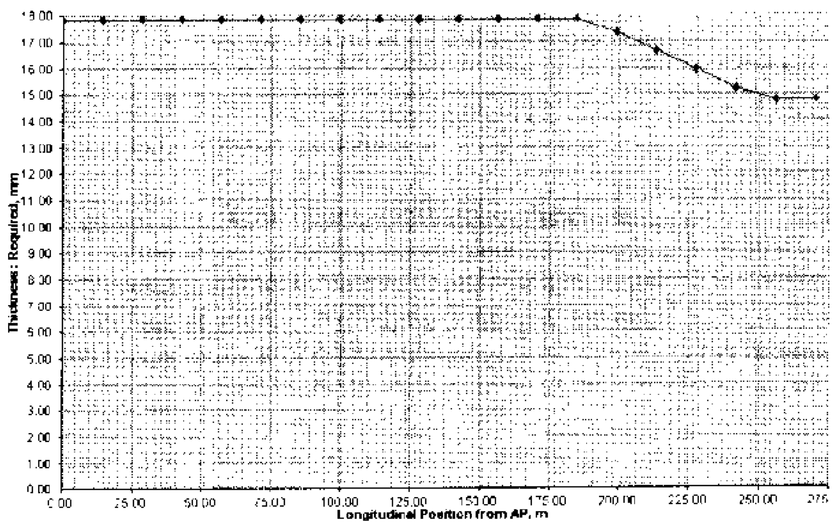
	Property	Units	Entered	Derived	Required
1	*Longitudinal Position from AP*	m	0.000		
2	*Region of Ship Under Consideration*			*Aft end*	
3	*Material*		Steel		
4	*Double Bottom Tanks Interconnected to side tanks or Cofferdams*		No		
5	*Ceiling Fitted in way of Hatchway*		Yes		
6	*Cargo to be Discharged by Grabs*		No		
7	*Tank Liquid Relative Density*		1.025		
8	*Load Head h4*	m	0.000		
9	*Primary Stiffener Spacing*	m	0.000	*3.000*	
10	*Secondary Stiffener Spacing*	mm	0.000	*800.000*	
11	*Maximum Hull Vertical Stress at Keel*	N/mm2	0.000		
12	*Load Height, h (double hull tankers)*	m	0.000		
13	*Distance, b1 (double hull oil tankers only)*	m	0.000		
14	*Thickness*	mm	0.000		[illegible]

In typical use a designer will enter the basic dimensions of the vessel, information on the materials being used, and details of the section profiles employed. Once the basic data has been entered structural items can be defined. For example the thickness requirement for inner bottom plating can be established at a particular location by providing only the following details:

- Longitudinal Position
- Material of Construction
- Tank load head
- Stiffener Spacing

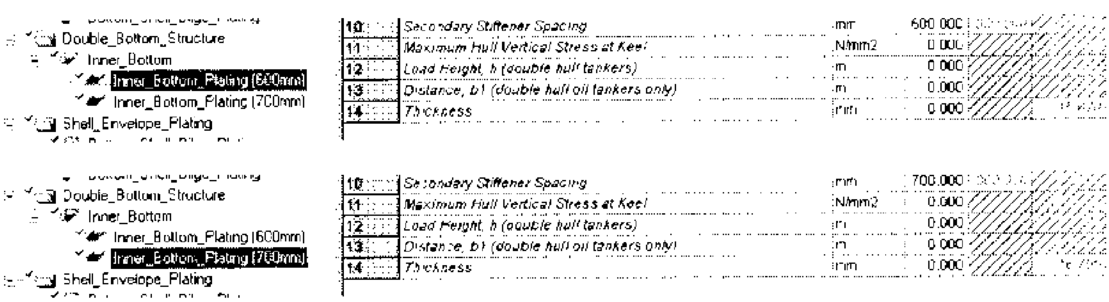
RulesCalc then provides the ability to establish the requirement over the whole length of the vessel using simple graphical tools.

Figure 6 : Graph showing thickness requirement over whole length



Alternative design choices can simply be investigated by creating another entry in the system for inner bottom plating. A user, for example, may investigate the effect of primary stiffener spacing on the thickness requirement.

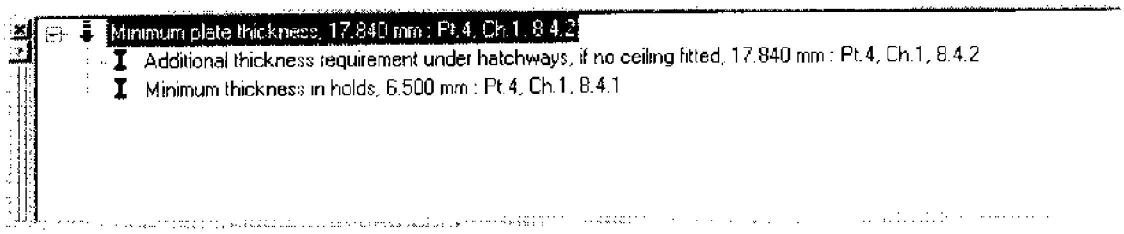
Figure 7 : Two experimental items for inner shell plating



Transparency

Another key element to understanding the requirements laid out in the Rules is information on how the final requirements are obtained. Knowledge and understanding of the requirements can improve the confidence in a design. The RulesCalc system assists with this in two ways, through providing information on both what calculations have been performed and what Rules have been applied.

Figure 8 : Intermediate Results



Calculation Transparency

To this end the RulesCalc system provides full details of all of the intermediate results that were performed to derive the final result.

In addition to providing the values of these intermediate factors, the system also provides a Rule Reference to enable the designer to look up the formulae in the Rules. Indeed the RulesCalc interface can jump directly to the actual Rule reference in an electronic version of the Rules.

This single feature provides a degree of transparency of results that has not been made available in Rule verification systems before.

Rule Transparency

The designer can clearly see what items are being assessed and which Rules have been applied to arrive at that assessment. By understanding the approval criteria and their application to the design, the designer is able to make decisions on improvements which can be accommodated within the Rule requirements. This important feature of RulesCalc assists in optimising the design more quickly and efficiently; and gives the designer a greater confidence that his changes will meet the Rule requirements.

Integration with Design Systems

Integration

Whilst this system provides a tool to enable very rapid scantling verification even more can be done to assist the designer to carry out classification checks.

The RulesCalc system has been written in such a manner that the calculations can be fully and seamlessly integrated with other design tools. This enables the design tool to evaluate continuously the components of the design and provide the user with the rule requirements along side actual values.

This powerful capability enables the naval architect for the first time to have continuous feedback on whether the design meets the classification requirements throughout the entire design process.

Fine Grained

In order to be able to make a useable system that offers full integration with a design system such that Rule calculations can proceed continuously, it is necessary to break the running of the calculations down so that the amount of input data required is kept to a minimum at any stage of the evaluation process and that the execution of the calculation completes as quickly as possible.

Since only the minimum amount of data required for any calculation is used the likelihood is that this data will be available sooner in the design process.

Data Model

In order to be able to communicate with the design system, RulesCalc must assume a data model which describes the various items (entities) that can be assessed and their properties (attributes). The model used is hierarchical and contains no complex associations. The implementation of this model within the design system is an important part of the integration with RulesCalc.

To minimise the work involved in this implementation the various entities in the model use common attributes wherever possible. To assist further full access is given to the model through a series of COM interfaces which provide information on entity names, valid children, attributes and subtypes.

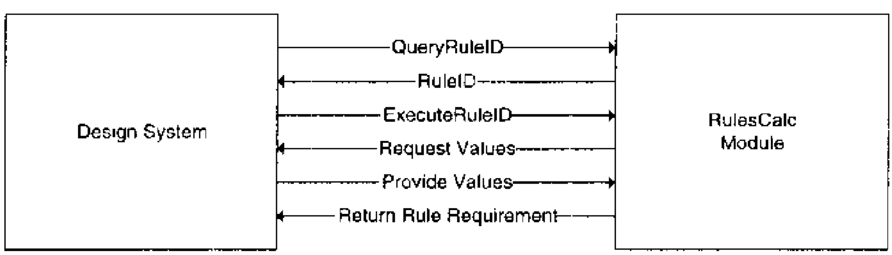
Programming Requirements

All communication between the design system and the Rule calculations occurs using just two simple COM interfaces.

The first interface (RuleEngine) provides a means for a design system to execute a particular Rule and contains just 3 methods. The second interface (RuleItem) provides a means for the Rules to request particular values from the design system. This is a more complex interface containing 14 methods.

Figure 9 below illustrates the typical steps taken to calculate a requirement.

Figure 9 : Process of Rule Execution



In order to perform a calculation the design system first queries for the id of the calculation based on the property and entity name, for example **required_section_modulus** attribute of a **transverse_section** entity. The design system may store this value for later use.

The calculation module will then return an ID number for the appropriate calculation. The client can use this number to execute this rule by calling ExecuteRuleID. The RulesCalc module will then request any values that are required in order to perform the calculation. This is the where the main element of work is required in the design systems. The interface must translate requests from the RulesCalc module into the appropriate data items stored in the design system. The design system should then return the requested value. The RulesCalc module may then ask for further values. The values requested may depend on the results of earlier requests. In this way only the minimum of data needs to be provided by the Design system rather than a large data set which covers all eventualities.

The calculation module then completes the calculations and returns the final rule requirement.

If the calculation derives any intermediate results these are also returned to the design system which may display or discard these results as it sees fit. The RulesCalc system will not ask for any of these values.

Error Handling

The RulesCalc system implements a simple, but powerful, error handling capability. When the module requests a value from its host the design system can reply with a error, e.g. indicate that the value requested is not available due to the user having not defined a particular piece of information.

If when performing the calculation any requested value has an error the calculation will be abandoned. The RulesCalc system will return the error code passed to it by the design system.

Additionally the RulesCalc system may return a error code as a result of the input data, for example to indicate that there was a divide by zero error. Again the calculation will terminate.

A further "error" condition is possible. If when performing a calculation the RulesCalc system decides that a particular Rule is not applicable, it will stop the calculation return a not applicable error.

Table 2 : RulesCalc Error Codes

ieOk	Calculation completed satisfactorily
ieNotapplicable	The calculation is not applicable in this case.
ieDivzero	There was a divide by zero error
ieRange	An input value was outside of the allowable range
ieReference	A requested value was not available

ShipRight ^{IS}

RulesCalc is being integrated within ShipRight^{IS}, LR's 3D product model based design assessment tool. This offers the user a system that enables a design to be developed from initial concepts, right through to finite element analysis inside a single package that utilises a single product model.

Conclusion

The RulesCalc system offers a solution to enable the ship designer to realise the complete benefits of concurrent classification checks, using either a fully integrated system or a standalone system supported by the minimum data entry approach.

This gives the designer the benefit of many years of classification design assessment experience as early in the design cycle as the concept stage.

The use of such a tool is a key element in improving the overall plan appraisal process, as the designer has a much increased level of confidence that the proposal meets with the basic classification requirements before it is submitted. That is to say that the design meets the minimum scantling requirements of the classification society.

This preliminary but important check can now be carried out before submission of the design; and reduces the need for the active involvement of a plan approval surveyor.

This improvement in the process has significant benefits to all parties, in terms of reduced time spent in plan appraisal and less effort spent in design modifications.

The ability to assess designs earlier in the design process can lead to reduced steel weights and hence construction costs, as designers are confident of the actual classification requirement and can optimise the design within those requirements more readily. RulesCalc will enable designers and builders to significantly reduce the time to market for new vessels.

EXCHANGE OF STRUCTURAL DESIGN MODELS FOR RULE APPROVAL BASED ON STEP

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Introduction

Computers in shipbuilding have improved the productivity together with the development of engineering design, analysis, and production automation. But within each specialized area or each department different computer systems are being used, because each system has own advantages and disadvantages. While the functions of individual CAD systems have been gradually improved, one CAD system can not support every specialty area. Therefore the phenomenon called *Island of Automation* [1] exists where diverse CAD systems are being used independently in each discipline. As a result engineering data management such as generation, storage, modification and exchange of engineering data has been a problem. As shown in Fig 1, different CAD systems are being used in the structural design office in a shipbuilding company. The data exchange between processes is neither harmonious nor automatic, and the data management becomes difficult.

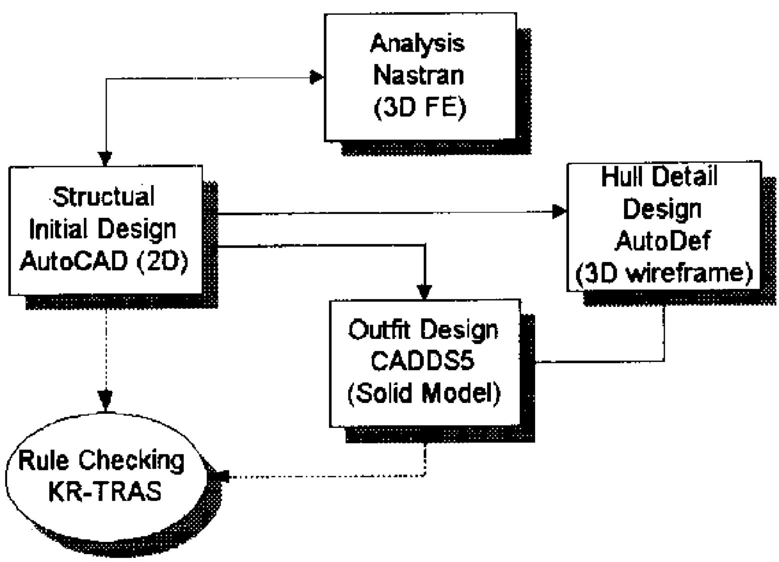


Fig 1. Flow of Structural Design Information

Korean Register of Shipping developed KR-TRAS (KR Technical Rule Approval System) [2], that is PC-based program for the review of ship structures and equipment according to the Rules of Korean Register of Shipping [3,4]. It offers information, which is used at each step of basic design, detail design, and outfit design in both shipyards and shipping companies. Fig 2 shows the overall structure of KR-TRAS. The relevant *Rules for Classification of Steel Ships* are applied according to the size and type of each ship, and KR-TRAS calculates individual part of the ship structure. However the designer should type in every data into dialog boxes in order to perform these computations. In this study, the drawing recognition system based on the STEP methodology [5] and KR-TRAS is integrated to automate this data input process. The whole process is; recognize features from 2D CAD drawing, build 3D shape, extract input variables for KR-TRAS, and additional manual input into KR-TRAS for the calculation.

The problem is the mapping between the data structure of KR-TRAS and the data structure of midship schema based on the BB(building block) of STEP, and the recognition of the shipbuilding features from 2D CAD drawings. Therefore techniques to increase recognition rate and to interface the drawing recognition system with KR-TRAS are required. From the literature survey, the design data to certify ship structures has been exchanged using STEP in the European SEASPRITE project [6]. The difference from this paper is that the completed ship model after the detail design has been used whereas this paper deals with the initial design stage.

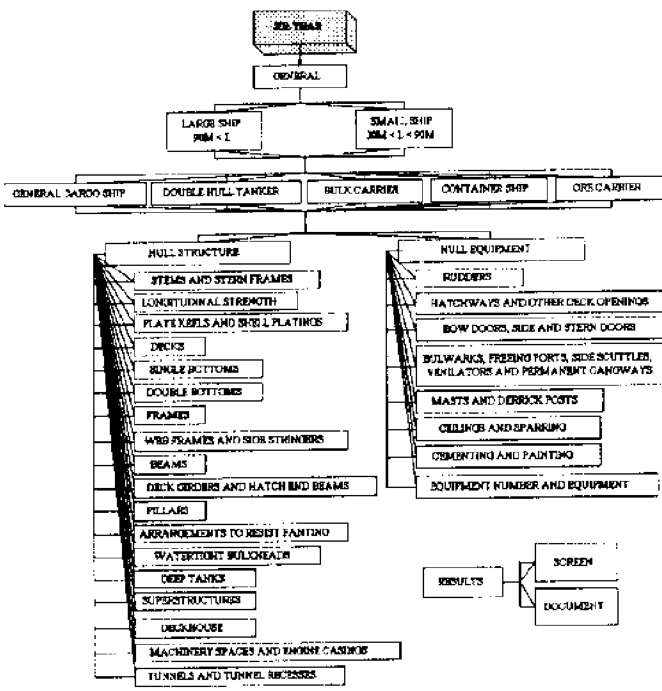


Fig 2. The Structure of KR-TRAS

Definition of the Midship Structure Model According to STEP

In order to represent a product model systematically and to realize an open architecture framework, the STEP methodology is utilized. A set of schema for the midship section of a bulk carrier has been defined by the EXPRESS information modeling language. It utilizes the shipbuilding BBs (Building Blocks) that are the bases of the shipbuilding APs (Application Protocols) of STEP. Using the same schema throughout the lifecycle from design up to manufacturing, integration, exchange, and sharing of engineering data can be achieved easily.

STEP Methodology

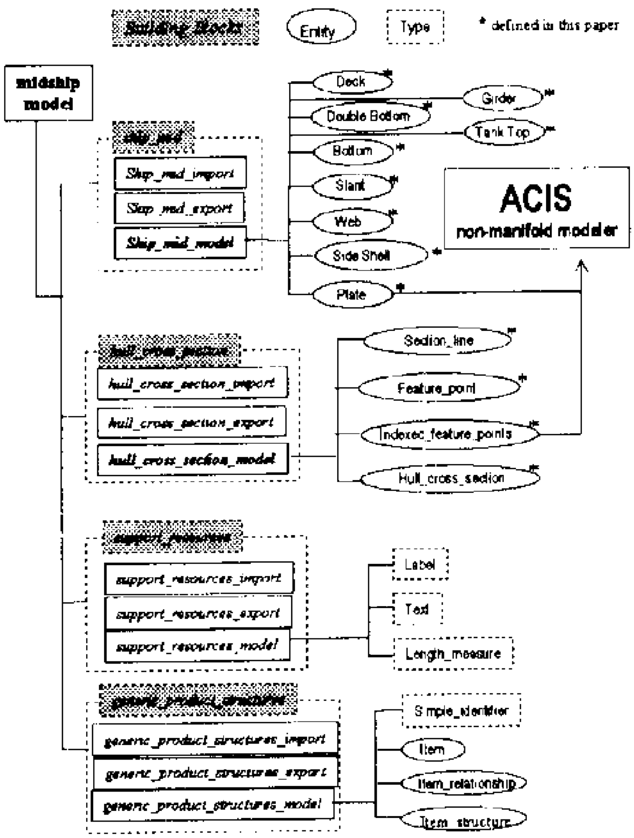
The STEP methodology provides an efficient environment to represent product model because STEP is object-oriented and modularized. The STEP standard consists of series of parts such as description methods (10s), implementation methods (20s), conformance testing methodology and framework (30s), integrated generic resources (40s), integrated application resources (100s), application protocols (200s), and abstract test suites (300s), and application interpreted constructs (500s), etc [7].

The STEP methodology separates the data structure from the data storage. If the data structure is defined by the EXPRESS information modeling language, the real data can be stored either as the Part 21 format of ASCII file [8], or as a database management system using the Part 22 SDAI (standard data access interface) [9]. The separation between the definition of data structure and the storage of data values helps to implement product models and to extend and to customize the models. A schema is the definition of the product model structure of a specific domain and is written by EXPRESS. Within a schema other schemas can be referred using the import sentence. As it can refer to other authenticated schema such as STEP AP203, a data model can be easily created.

Schema for the Midship Structure Model

The structural model schema defined in this paper consists of four BBs (Building Blocks) as Fig 3. Each BB consists of three schemas called export, import, and model. The BB methodology constructs a product model by collecting several independent BBs. In case of the product like ship, which has tremendous data contents and different viewpoints, different people can construct a portion of ship product model in parallel. Among above four BBs, *ship_mid_model* is newly defined in this research. *hull_cross_section_model* comes from the BBs of EMSA (European marine STEP association) [10], which is modified to accommodate 2D midship cross section data. And the other two schemas, *support_resources_model* and *generic_product_structures_model* are extracted from the EMSA BBs.

Fig 3. Midship model schema and entities



In *hull_cross_section_model*, there is *section_line* entity to represent 2D line entities. *feature_point* represents characteristic points of the midship cross section, *indexed_feature_points* defines midship cross sections for each type of ship, and *hull_cross_section* entity holds shipbuilding features such as deck, side shell, and girder. From *section_line* where line entities from 2D drawing are stored, *feature_point* which determines typical midship section is found, and *indexed_feature_points* is constructed. From *indexed_feature_points*, shipbuilding feature is created and stored in *hull_cross_section*. The recognized *hull_corss_section* entity creates 3D plate entities defined in the model schema of *ship_mid_model* BB and is transferred to the ACIS non-manifold model.

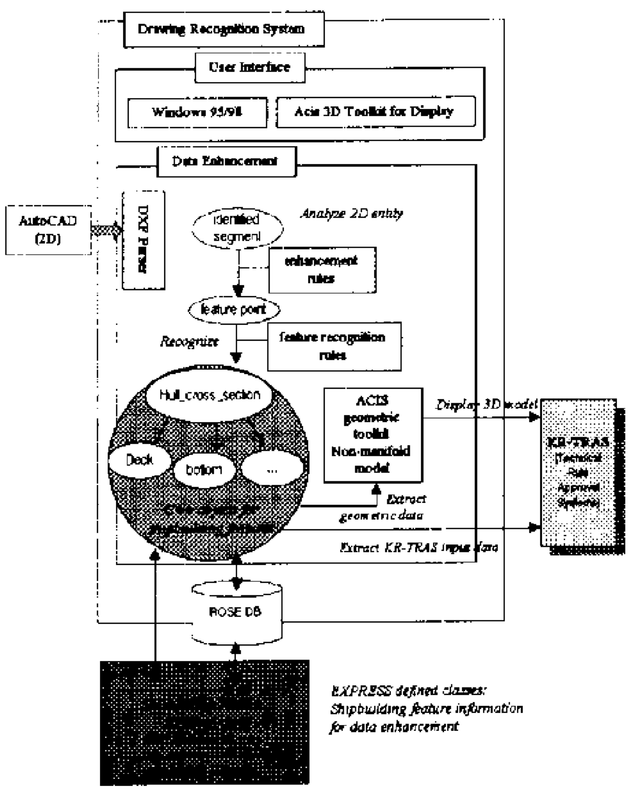
In the near future, as the application protocol AP218 that standardizes the ship structure is completed, it is more desirable to use the midship cross section schema of AP218 as the backbone schema.

Implementation of the System

Overview of the Implemented System

Fig 4 shows the integrated result of the drawing recognition system with KR-TRAS. This system analyzes and enhances the 2D drawing and certifies the design according to the KR rules. The system is implemented in Windows 95/98 platform and uses the ACIS class library to handle geometric data. The ACIS toolkit supports the non-manifold geometric modeling to process low-level geometric operations. The STEP toolkit *ST-Developer* and ROSE database is adopted to manipulate the ship design data instantiated from EXPRESS. The midship schema is constructed according to the STEP methodology. The non-manifold geometric modeling technology and the feature recognition methodology are utilized to manipulate the ship design data such as modification, mapping, and addition of data. The input data required for the variables of KR-TRAS are extracted and passed into KR-TRAS, and so the structural design is certified according to the Rules of Korean Register of Shipping.

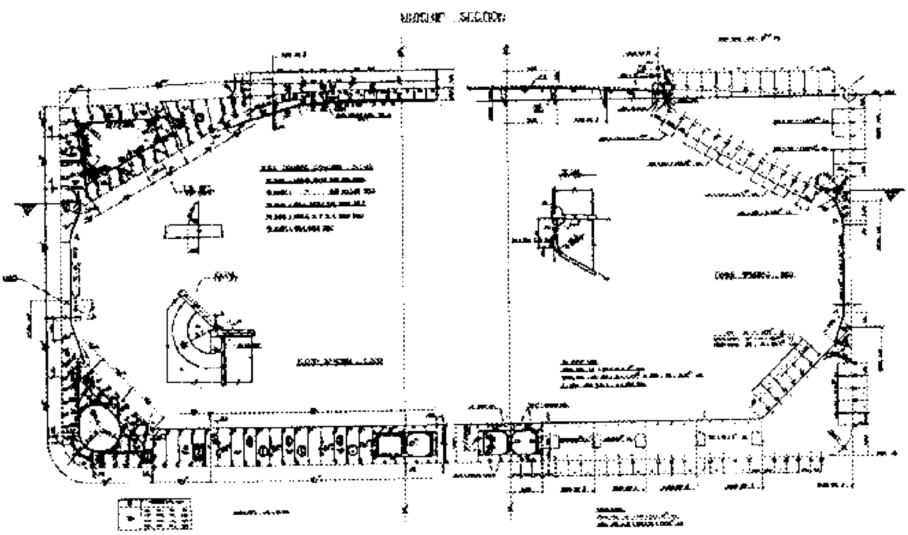
Fig 4. Interfacing the Drawing Recognition System with KR-TRAS



Recognition of Midship Section Drawing

Fig 5 shows a typical midship section drawing of a bulk carrier. It is stored as DXF ASCII formats. A DXF file [11] is composed of pairs of codes and associated values. The codes, known as *group codes*, indicate the type of value that follows. Using these group codes and value pairs, a DXF file is organized into the following sections. Sections are composed of records, which are further decomposed into group codes and data items.

Fig 5. Midship Section Drawing of a Bulk Carrier Designed by AutoCAD



1 HEADER section : General information about the drawing is found in this section. It consists of an AutoCAD database version number and a number of system variables. Each parameter contains a variable name and its associated value.

2 TABLES section : This section represents the named objects and contains definitions for the following symbol tables. Line type table, Layer table, Style table, View table, User Coordinate System table, Viewport configuration table, Dimension Style table, Application Identification table

3 BLOCKS section : Contains block definition and drawing entities that make up each block reference in the drawing.

4 ENTITIES section : This section contains the graphical objects (entities) in the drawing, including block references (insert entities).

5 END section : tells the end of the file .

This file format has group codes and values for each entity, and the TABLE sections have been analyzed to extract attributes of LINE and ARC entities. For LINE entities the coordinate values of the start and the end points are extracted. For ARC entities, the coordinate values of the midpoint, the start angle, and the end angle are extracted. Heuristic rules for the feature recognition have been applied to the extracted lines and arcs to construct a 3D model. According to the recognition rules of midship section (Table 1), deck, side shell, bottom, inner bottom, slant, and girder are extracted and recognized as the 3D elements. For example, among the highest (upper), the longest and the 10% inclined line of the extracted lines is recognized as the deck.

Table 1. Feature Recognition Rules

Feature	H-Location	V-Location	Length	Direction
DECK	1^{ST} UP	LEFT	LONGEST	10 % INCLINED
SSHELL		LEFT	LONGEST	VERTICAL
BOTTOM	1^{ST} DOWN	LEFT	LONGEST	HORIZONTAL
IN-BOTTOM	2^{ND} DOWN	LEFT	LONGEST	HORIZONTAL
GIRDER	DOWN	LEFT		VERTICAL
TTOP	2^{ND} UP	LEFT		50% INCLINED
SLANT	DOWN	LEFT		50% INCLINED

The recognized feature model is visualized as a 3D model using the geometric modeling toolkit ACIS. Fig 6 shows the recognized 3D model of the midship section. ACIS allows mixed dimensional models including 2D, 3D, wireframe, and solid models. It has an advantage that both the wireframe model of the early design stage and the solid model of the production design stage can be saved and managed under one data structure.

After constructing a 3D model using the features recognized from the 2D drawings, we extracted the variables for KR-TRAS. The information of each plate is gathered with the drawing recognition system, then the input variables of KR-TRAS are found. Table 2 lists the variables of KR-TRAS that can be extracted from 2D drawings. Because a plate consists of many pieces, seam lines are represented on the drawing. To verify the design with KR-TRAS, we should find the seam lines because we need not only the data of the whole plate but also the data of pieces. The recognized data is then transformed according to the variable types. Among the input variables of KR-TRAS the coordinates, length, and thickness of the plate can be easily found. For the variables representing distances between horizontal and vertical diameters of the girder opening or the largest value among stiffener spaces of longitudinal frames, which are attached on the girder, the information of the feature should be parsed twice.

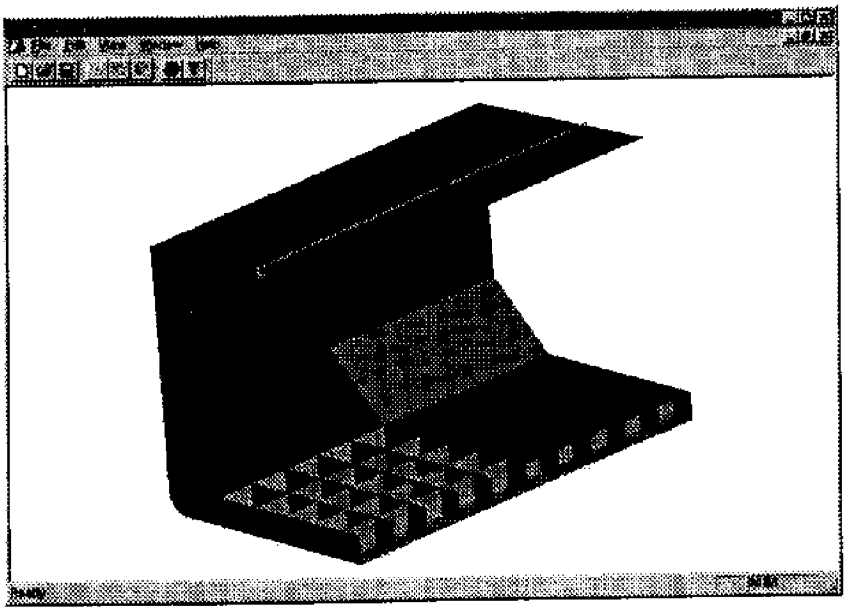


Fig 6. Recognized 3D Model of Midship Section

The system can recognize 36 variables (including arrays) from the drawings among the 200 input variables of KR-TRAS. These variables are mostly the coordinates and lengths of the plates.

Implementation Results

The following are implemented in this research.

(1) A STEP protocol for structural design model of midship section has been developed based on the STEP methodology. Information modeling with EXPRESS language enables systematic definition of data structure and maintains the consistent data structure from the 2D drawing of initial design to the 3D solid model of detail design.

(2) 3D features have been extracted by applying the feature recognition rules to 2D design drawing data.

Table 2. Input Variables of KR-TRAS

	Variable Name	Type	Description
1	M_PlateIdno[30]	Int	Total number of each plate
2	M_PlateMat[30][31]	Int	Material factor of each plate
3	M_PlateX1[30][31]	Double	start X coordinate of each plate
4	M_PlateY1[30][31]	Double	start Y coordinate of each plate
5	M_PlateX2[30][31]	Double	end X coordinate of each plate
6	M_PlateY2[30][31]	Double	end Y coordinate of each plate
7	M_PlateActThk[30][31]	Double	actual thickness of each plate
8	M_PlateRad[30][31]	Double	radius of each plate
9	M_PlateBilgeX	Double	Center X coordinate of Bilge plate
10	M_PlateBilgeY	Double	Center Y coordinate of Bilge plate
11	M_PlateSheerX	Double	Center X coordinate of Sheer strake

(3) The recognized features have been converted as non-manifold models. Non-manifold models are used in order to process the geometric data represented differently on each system. A standard neutral format such as STEP can solve the problem derived from functional differences among design systems.

(4) The variables were extracted and carried to KR-TRAS for the calculation to check the *rules and guidance for classification of steel ships*. The menu 'import DXF' has been added to existing menu of KR-TRAS so that a 2D drawing of DXF format can be read. As a set of drawing data is put into the system, lines and arcs are extracted and saved in the database. According to the pre-defined feature recognition rules the features such as deck, bottom, longitudinal, and seam lines are recognized from the lines and arcs. Using the recognized features the 3D models can be generated and visualized. The data required for calculation of KR-TRAS are provided to the variables of KR-TRAS. A designer can confirm how the 2D drawings are converted to 3D models. Fig 7 shows the user interface of the integration of the drawing recognition system with KR-TRAS system.

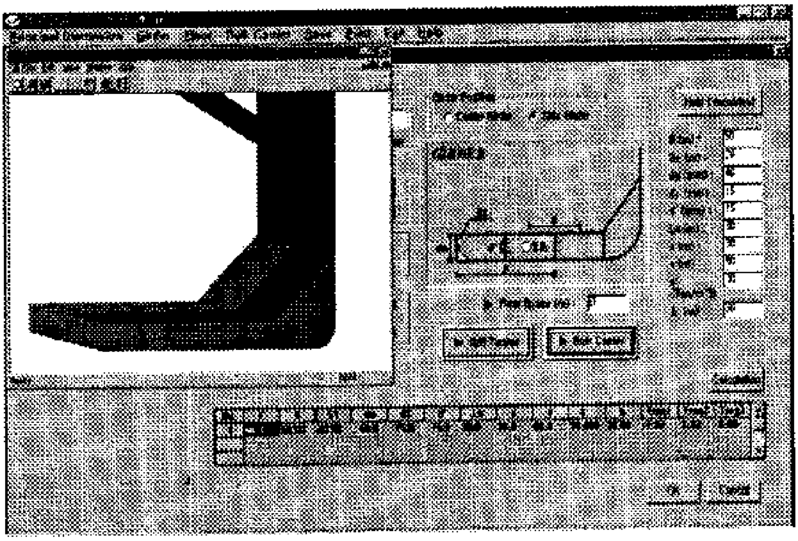


Fig 7. The Integration of the Drawing Recognition System with KR-TRAS

Conclusion

In this research the hull structural model of neutral format has been constructed to share the data among CAD systems of functional differences. We developed the system to analyze the 2D structural design data according to the feature recognition rules and convert them to 3D non-manifold models for downstream applications. This drawing recognition system has been interfaced with KR-TRAS (KR Technical Rule Approval System), a PC-based computer program for design scantling and review of ship structures and equipment according to the rules of KR(Korean Register of Shipping).

Because STEP methodology is utilized to define the model of this system, it is possible to share the data consistently and systematically when the 2D drawing data of initial design stage are transmitted to the downstream stages such as detail design or outfit design.

In this research, only the length and the orientation of a 2D line are considered to define shipbuilding features. If more information may be added during the initial design stage, such as layer, line color, and line thickness, more design entities can be recognized systematically. In order to recognize lines that represent scaled-down entities such as longitudinal stiffeners, pre-defined specifications of the entities have to be included as shipbuilding features. The texts such as dimensions are saved also as ASCII format in DXF drawings. Therefore, recognizing the texts with graphic entities enables more exact recognition of design drawings. If the recognition rate is high, a fair amount of work repeated at the next stages can also be reduced. Data mismatch between design stages or between design departments can be avoided. The more exact recognition from 2D drawings can be done, the more data correspond to the input variables of KR-TRAS can be extracted.

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TOOLS FOR THE ASSESSMENT OF SHIP STRUCTURAL STEELWORKS - A STATE OF THE ART SURVEY

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Abstract

The ship structure design, assessment and approval process chain is described. Tools available to support this iterative process are categorised according their principal functionality. An evaluation scheme is presented which serves to analyse and compare the functionality of software systems made available by the major classification societies. Some of the tools are described following the developed scheme which gives an overview of the products. This indicates different strategies followed by the classification societies. Emphasis is given on the possibilities to model the ship structural components and piece parts and to integrate the "stand alone" software in the existing tool environment at shipyards and design agents. The described criteria can serve for future evaluations to be performed, taking into account own specific requirements as well as the ongoing and rapid development of the class supplied structure assessment tools.

Introduction

Design and production of ships today is supported by a large variety of software tools. Each of these tools focus on a specific task to be performed. Some allow for an integrated process either by being based on the same data management component or by offering data exchange functions with help of interfaces to import and export data. Whereas for example for hydrostatic calculations or detailed design tools are used at shipyards for more than 25 years, specialised software for the assessment of the ship structural steelworks according to the classification society rule requirements and direct calculations has almost not been available until some years ago. At that time, classification societies started to market software which is claimed to be specially designed to be used by their clients to ease the design process and to speed up the class approval process which in almost all cases is critical due to the short time available. Some of the driving forces are:

- Traditionally, the preliminary structural design is based on the construction rules of the classification societies, the observance of this framework automatically leads to structural integrity. The new and often very advanced ship designs can not be verified only based on these rules any more. Due to the complexity of the design, rationally based design or first principal design strategies have to be applied which require corresponding software tools to be used.
- For all tasks to be performed in the design of the ship, software is available almost except for the assessment of the structural steelwork according to class requirements. With the increasing demand on having available most reliable information about the vessel already in the pre-contract phase, the determination of scantlings and e.g. accurate weight distribution has migrated to earlier design stages. As at that time the conceptual design still undergoes major changes, tools are required for a flexible calculation of the fundamental information to be used in the cost estimate.
- To stay competitive, shipyards try to shorten the time to market which, among other aspects, can be achieved by an increased productivity. This asks for less and less time necessary and a higher overlap between all design and production process steps. Ito et al. [1] give a breakdown of the resources needed for the hull structural design work. According to their results, about 20% of the

overall time is spent for strength analysis and calculations with respect to rules and standards. Furthermore it has to be noted that the ordering of steel material requires reliable information on the structural steelwork. In this context, the approval of the design often turns out to be a bottleneck in the process chain. To overcome the sometimes critical situation, shipyards ask for an optimal and streamlined design approval which classification societies take up and try to support with help of their newly developed software tools.

- In many shipyards the few highly qualified and experienced engineers with deep knowledge on ship structures are often responsible for many tasks to be performed. The consequence is not enough time available for a thorough design analysis. It is believed that software tools "incorporate" the required knowledge and their usage will allow less qualified personnel to perform the design.
- Classification societies keep changing the role they had for more than hundred years. To gain market shares they are today taking a more active position while offering services to their clients which until some years ago were only supplied by engineering offices and design agents or software vendors. Many programs exist for a long time to support the classification society internal design approval. The new software aims more on the design and, at the same time, at the check against classification requirements.

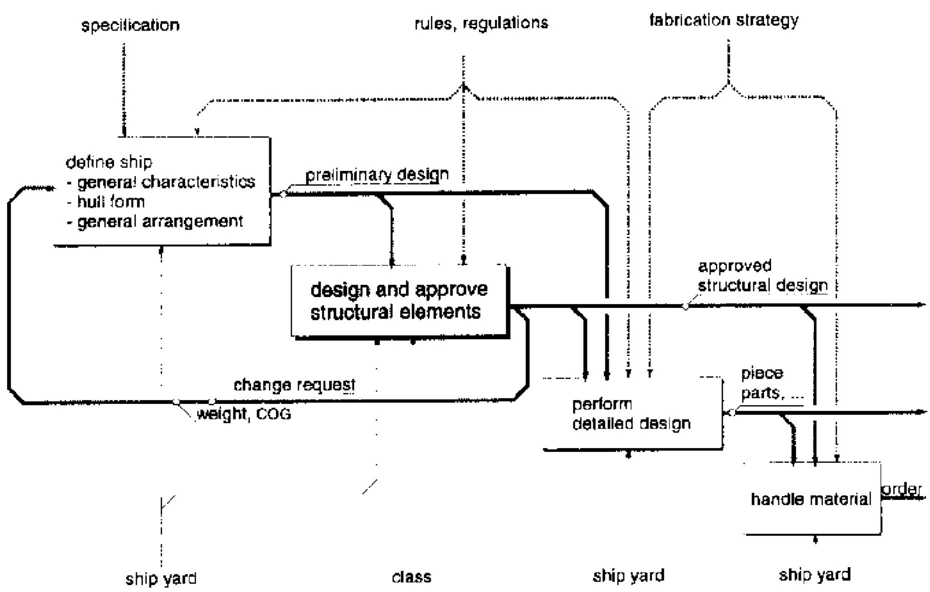

Figure 1. Ship Structure Design Process

As class societies market their new software tools to perform the dimensioning of the steel structure and to support the approval process, the working environment for the designer has changed and will continue to change. Shipyards build ships according to the rules and regulations of different classification societies. Until some years ago, this resulted in that the designer had to observe different rules, approval strategies and procedures. Today the situation has changed in that different complex software systems have to be used for the same task to be performed.

An overview of some systems available is given. Even though the designer is not always free to choose from the tools available (some classification societies strongly recommend or even force the usage of their software), the catalogue of the evaluation criteria can help to find an optimal strategy.

Ship Structure Design and Approval

The ship structure design and approval process is discussed to give a background for the tools being described.

Figure 1 shows how the different activities are embedded in the overall steel structural design. Design, assessment and approval is performed in an iterative process. The required input to this task is the preliminary design: ship general characteristics, hull form and general arrangement. The task is controlled by the rules and regulations to be fulfilled, most of them are released by the classification societies.

The results (output) are:

- possible change requests which might even cause modifications to the general arrangement,
- an approved structure definition which forms the basis for the material ordering and the detailed design,
- accurate weight distribution and reliable centre of gravity of the ship steel structure which are required for the deadweight and ship stability calculations.

A closer look on activity "design and approve structural elements" is given in **Figure 2**. The three principally different tasks: structure definition, structure analysis according to rules and structure analysis according to direct calculations are depicted as well as the corresponding relationships:

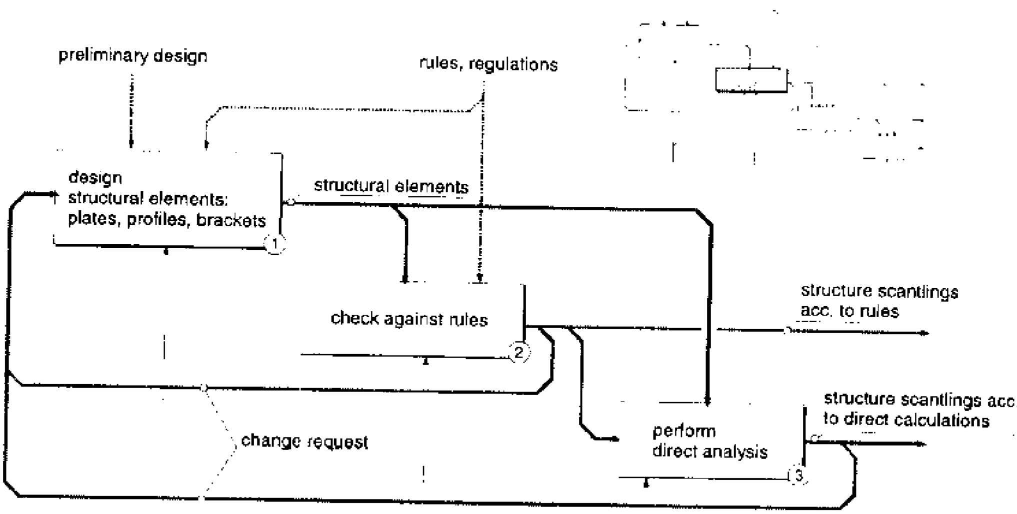

Figure 2. Ship Structure Assessment – Approval Process

- The layout of the structural elements has to fulfil the requirements defined in the preliminary design, two most important information are the hull form and the spatial subdivision which have to be realised by the structural elements.
- The approval according to class society rules i.e. minimum hull cross sectional properties as well as minimum scantlings of plates and stiffeners has to take into account the loads on the structure which are either calculated based on the class rules or which result out of the vessel's specification for deck loads and the general arrangement for tank loads.

Cabos et al. [2] give a comprehensive list of aspects which have to be considered for a rationally based structural design: 3D model of the ship structure, realistic sea loads (waves), direct calculation method (FEM), limit state analysis (deflection, fracture, buckling, ...), reliability based safety factors, formulation of "failure equations" and possibly other design constraints and optimisation algorithms using specified optimisation objectives.

- The very important input to rationally based design is a 3-D model of the ship structure for which in the first iteration step the scantlings of the piece parts can be defined according the class rule requirements. The results again might ask for local or even global changes of the structural design. Finally, all relevant scantlings are determined – approved by class – and serve as input to the downstream design and production process steps.

The specially developed software tools for the support of the assessment and approval of ship structures have to be analysed and measured against the following statements which summarise the given overview:

1. Design and approval is an iterative process to be performed in a short time span and in close co-operation between shipyard (design agent) and classification society.
2. The information required is generated with help of specialised CAD-systems which to a certain extend focus on naval architecture calculations.
3. The results of the assessment and approval add to the input in that the structure is defined in more detail. This forms the fundamental basis for the final ship general characteristics, the general arrangement which in turn allow for an early and reliable cost estimate, for material ordering and the detailed design of the piece parts the structure is to be built of.
4. In many cases direct calculations have to be performed as the structural configuration can not be analysed according to rules only.

Tools for the Assessment of the Ship Structural Steelwork

Software tools to support the assessment of the ship structure can be classified into the following categories:

1. hypertext based rule search and presentation,
2. calculation of scantlings of simple or complex structural configurations according to rule requirements,
3. calculation of scantlings of structural elements which contribute to hull cross sectional properties (longitudinal strength),
4. 3-D modelling of parts of the structure or the complete ship and direct calculation methods,
5. interfaces for a data exchange between design and analysis tools.

Hypertext Rule Presentation

A rule presentation based on hypertext functions adds some extra functionality compared to the printed rule books. A major advantage are the built-in search facilities which in many implementations do a full text search and highlight chapters which include regulations or comments for the specified criteria. This often leaves it to the user to find out the relevant rules in the specific context. The navigation in the text is easy as cross references can be followed by links. Programs belonging to this category are for example:

- Electronic Rulebook by Det Norske Veritas,
- GL-Rules by Germanischer Lloyd,
- KR-Rules by Korean Register of Shipping,
- RuleFinder by Lloyd's Register of Shipping which offers the most complete set of rules and regu-

lations and the most advanced functionality for searching. An index system can be used to restrict the result of even complex search criteria applying filters like ship type, flag state, principal dates or class notations.

Local Scantlings Calculation

Some classification societies offer programs which allow for a calculation of single plates or stiffeners or structural functional components (e.g. rudder) according to their rules. The user is guided through the corresponding rules via a spreadsheet or dialog style user interface. Apart from global data describing the ship like type, main characteristics etc. which may be stored for usage in different sessions, the user has to manually input all information which is necessary to calculate the scantlings of the structural component, the single plate or stiffener: e.g. thickness and required material grade of a floor plate, cross sectional properties for a stiffener on the side shell.

2-D Analysis – Hull Cross Section

The calculation of the hull cross sectional properties is to be performed for almost any ship and has to be approved according to the IACS unified requirements regarding the minimum section modulus and moment of inertia. To speed up this task, tools of different functionality exist. Some simply calculate the cross sectional data based on the user defined input of the structural arrangement and dimensions of piece parts making up the cross section. Other also check piece parts for compliance with the rules regarding local strength requirements based on "rule loads". In these cases, combined stresses due to the hull bending moment and due to locally acting loads are taken into account.

To be able to perform the analysis, the complete cross sections of the hull structure at the longitudinal positions of interest have to be modelled. All plate and profile shape parameter and material properties have to be defined. For the local strength calculation, three dimensional data have to be specified as well like unsupported span of plates and profiles in longitudinal direction. Furthermore, the tank configuration and deck loads given in the vessel's specification have to be defined for the automated calculation of locally acting loads on the structural elements. To allow the program to apply the correct rules, all components have to be given a type identifier or rule designation, examples are: deck, side shell, inner bottom, longitudinal bottom girder, ...

Many classification societies offer tools to perform this kind of analysis. As the final result, the approved hull cross section(s) is of utmost importance for the classification of the ship structural design, the different strategies and implemented working procedures are discussed below.

3-D Analysis – Direct calculations

The analysis with help of software of the third category is mainly based on a two-dimensional model of the ship structure. For many ship types this is not sufficient as it is necessary to perform an analysis which has to take the three-dimensional structural configuration into account, e.g. container ships with large deck openings, bulk carrier, ... Different strategies for this are offered by the tools available or under development, see below.

Integrating CAD and Analysis/Approval Software

Whereas software of the first four categories represent tools which can be used stand alone, the interfacing of design and analysis or approval programs is a strategic approach which leads to an integrated engineering workbench supplying the user with the functions necessary to design the ship. Until today the focus is on the development of the software for an "optimal" structure analysis and at the same time structure approval. Some of the systems available offer interfaces which to a limited extent allow for a data exchange. The potential of this approach is clearly seen by all classification societies and software vendors which has led to many R&D projects, for the strategies followed see below.

Evaluation Criteria

The criteria applied to evaluate software systems are introduced. The formulated and explained questions help to analyse the functionality offered. The description of the ship structure design and approval process, see **Figure 1** and **2**, serves as a guideline as the formulated requirements and boundary conditions have to be met by the tools.

To what category does the program or system belong?

Each software may be classified according the categories described. In some systems several components exist which serve different functions. In these cases, special attention should be given on how the components relate to each other. This directly leads to the next question:

What is the general philosophy?

In case of tools for the calculation of scantlings, either local or global view, the working procedure implemented and thus to be followed by the user should be looked at thoroughly. In this context, further questions going into more detail are:

? *Can the system be used for any ship type (generic) or do restrictions apply which limit the usage to specific types, for instance tanker, bulk carrier, container ships?*

? *Does the system support two- and/or three-dimensional ship structure models to be used for the assessment of the scantlings?*

? *Are all components of the structure covered by the software? Are restrictions given which limit the usage to special types of elements, e.g. longitudinally oriented or to regions like 0.4L midships?*

? *Is the user free to choose a working procedure or is there a restrictive path given to be followed in any case?*

How does the software support the design process?

As many of the tools supplied by the classification societies have their roots going back to the class internal design approval tasks, emphasis should be given on how the iterative process as described is supported. Further questions in this context are:

? *What is the overall functionality offered?*

The following may be looked for:

- ✓ Minimum scantlings according to rules
- ✓ Stresses and displacements based on direct calculations
- ✓ Limit state analysis: first principal design
- ✓ Vibration analysis (eigenvalues)
- ✓ Fatigue design assessment
- ✓ Weight and COG as input to naval architecture calculations

? *What is the (minimal) input required?*

This is important to know when trying to make use of the software as early as possible in the process chain.

? *Is an optimisation with respect to user defined objectives supported?*

Optimisation in many cases is an essential part of the design process. Due to the complexity of the structural components and their manifold relationships as well as the complex loads to be applied, optimisation functions have to be regarded as an advantageous feature.

? *How are modifications of the structure handled?*

The iterative working procedure in ship structural design and assessment leads to modifications of the structural design either caused by results out of the structural assessment itself or by changes of the general arrangement or even the vessel's characteristics. In this context it is important to automatically keep the product model consistent and though minimise errors.

How is the structural steelwork to be modelled?

The program internal representation of the structure has to be defined by the user. In this context different aspects have to be considered:

? *Does the system support 2-D, 3-D models or even multiple views on the structure?*
For a check against minimum values of cross section properties, rule based structural assessment requires a 2D cross section view on the hull structure. Direct calculations however have to be based on a 3D-model. In case of functions built-in which support both aspects:

? *How are 2-D and 3-D views managed?*
Principally two different strategies exist: the 2-D cross section is generated using a 3-D model or the 3-D model is generated based on 2-D hull structure descriptions. The first method has the advantage that an unambiguous representation exists. It should be noted however that even though mathematically exactly possible, the generation of 2-D views can not be performed fully automatically. The relevance and contribution of components to e.g. longitudinal strength can not in all cases be decided upon without the designer's knowledge to be taken into account.
The second method has the advantage that in a first step less input is required. The major drawback is to be seen in the fact that there is no unique way to automatically generate a precise 3-D model based on the 2-D views. In **Figure 3** the two approaches are depicted. The structural element in this case has a complex shape which obviously can not be generated out of the corresponding cross sectional representation which is a straight line. It is apparent that the 2-D representation can be generated when the 3-D model exists and the simple additional information is given at what position the cross section is asked for. It is however left to the user to judge upon the relevance of this structural part for the analysis under consideration.

? *Does the built-in product model support functional structural elements?*
The modelling and modifications of the structural model are less time consuming and prone to errors if a functional and an additional piece part view are managed by the software. In this case, plates and stiffeners are assigned to functional elements which represent structural components e.g. deck, shell, inner bottom, and by this inherit all relevant attributes of the corresponding element.

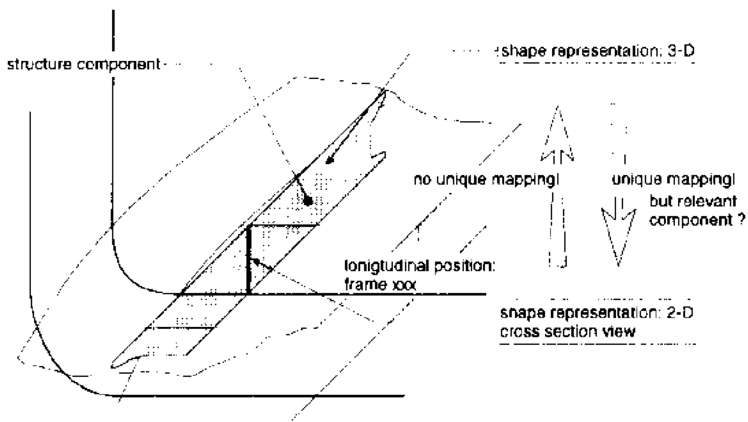

Figure 3. 2-D and 3-D Shape Representation of Structure Components

? *Is a parametric and associative modelling supported?*
The modelling and modifications of the structural model are less time consuming and prone to errors if the shape of the structural elements can be defined using associations between these elements. Some associations between functional elements and between piece parts are shown in **Figure 4.** In addition, the definition of centre and height of the cut-out in the floor plate is an example for parametric modelling. In case of modifications, the consistency of the structural model is retained if the associations and parametric definitions are part of the product model stored. The location or shape of any element describing the structural steelwork should be allowed to be defined with reference to an underlying frame grid. This associative definition is more suitable than using absolute length measures. Modification again are much easier to manage.

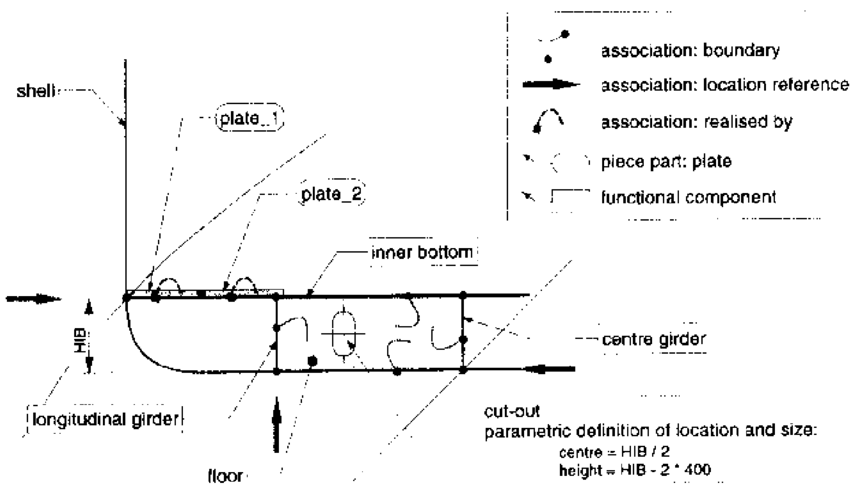

Figure 4. Associative and Parametric Structure Definition

? *How is symmetry handled?*
Many but not necessarily all structural elements are symmetrical to the ship centre plane (port and starboard side). Even though this aspect seems to be of minor importance, it might turn out to play a major role in the structure modelling if the functionality offered in this context does not allow to handle symmetrical and unsymmetrical elements properly.

? *What possibilities exist to reuse structural component definitions?*
Many of the ship structural components are identical in terms of an associative or parametric shape description but are located at different positions. For an efficient modelling it should be possible to make use of this fact. Necessary modifications of an element which is part of a set of "identical" ones might cause severe problems if the required functionality is not offered by the software implementation.

How are loads taken into consideration?

Loads acting on the structure may be classified in: loads as defined in the rules of the classification societies, loads as defined in the vessel's specification which might override class requirements (stack loads, deck loads), sea loads due to the ship motion in waves and loads imposed by the liquid motion in partially filled tanks.

How can the system be integrated into an existing software environment?

The necessity to integrate a tool for the assessment of the ship structure in the ship design and production process chain is obvious. The integration can be realised in different ways:

- interfaces for the import and export of information,
- interfaces which allow for a direct integration into other programs (application program interface (API)).

For a more detailed discussion of this most relevant topic please refer to the corresponding discussion of the software packages below.

Additional criteria

Additional criteria to be looked at but considered of less importance in this evaluation and though not further discussed are e.g. operating software and hardware requirements. The user interface offered by the software is worth a separate analyses but is not further discussed here.

Tools Versus Criteria

Software tools of classification societies are listed in **Table 1**. Due to the ongoing and rapid development, the reader has to be aware of the fact that new versions might exist in short time with major differences to the functionality described in this paper. It is not the intention to benchmark the systems which would result in some sort of rating.

Table 1. Classification Society Tools

Vendor	Product	URL (www. +)
American Bureau of Shipping (ABS)	ABS SafeHull	abs-group.com
Bureau Veritas (BV)	VeriSTAR	veristar.com
Det Norske Veritas (DNV)	Electronic Rulebook	dnv.com/dnvsoftware
	NAUTICUS HULL	
Germanischer Lloyd (GL)	GL-Rules	germanlloyd.org
	POSEIDON	
Korean Register of Shipping (KRS)	KR-RULES	krs.co.kr/md/services_e
	KR-TRAS	
Lloyd's Register of Shipping (LR)	Rulefinder	lr.org/software/shipright
	ShipRight	
Nippon Kaiji Kyokai (NKK)	PrimeShip BOSUN	classnk.or.jp/primeship/software

SafeHull (ABS)

The ABS SafeHull system by the American Bureau of Shipping is composed of two parts: the first of which is the requirements laid down in the Rules, the second part is the related software which is to be used in two phases:

- *Phase A*: to establish initial minimal required scantlings, considering hull-girder longitudinal bending and shear strength, local strength of plates and stiffeners, strength of main supporting members as well as fatigue assessment.
- *Phase B*: direct calculations based on finite element analysis methods to assess the strength of major portions of the hull to confirm the results of Phase A.

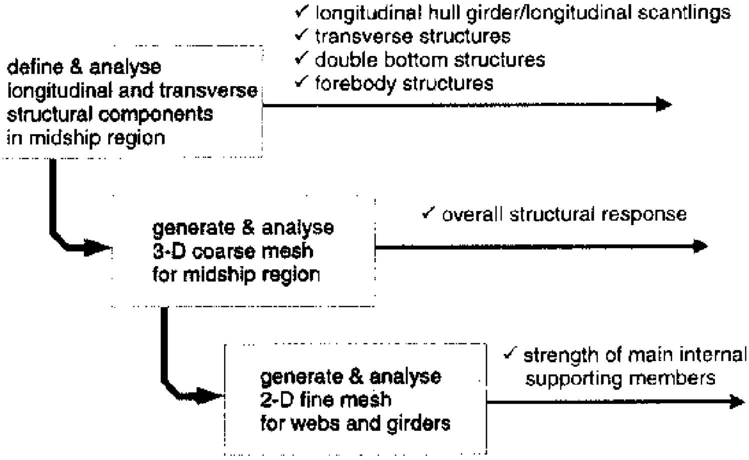

Figure 5. ABS SafeHull Workflow

The software is set up into modules to be used for different ship types: bulk carriers, tankers and container ships. The shape (geometry) for e.g. bulk carriers is taken constant for the 0.4L midship region. The layout of the longitudinal and transverse structural components is defined using a minimal set of parameter while symmetry with respect to the ship centre plane is assumed. The thickness of plates, realising the underlying structural components (functional elements) has to be defined by the user. Stiffeners are located referring to plates, the cross sectional properties are also to be defined by the user by selecting from a library. These parameter can be compared to the calculated required values, necessary changes have to be done manually. Additional functions are offered e.g. for bulk carriers the calculation of scantlings in the forebody region, a simplified fatigue assessment of selected members and a check against IACS structural requirements.

The direct analysis in *Phase B* is performed using a 3-D coarse mesh model (optionally output of *Phase A*) to assess the overall structural response and 2-D fine mesh models for transverse and longitudinal main members (web, girder). For the 2-D analysis selected portions of the 3-D coarse model are fine meshed automatically and further edited manually. Built-in solver, pre- and post-processor can be used or any other software which supports NASTRAN formatted file syntax for models.

All information managed by the ABS SafeHull system is stored in files. The contents and syntax is explained in a data reference manual. A data exchange can be realised based on these files.

Nauticus (DNV)

The Nauticus Hull system of Det Norske Veritas is planned to be offered in four packages of which the first "Nauticus Hull Rule Check" is released. The other packages add functions for a 3-D modelling and structure analysis as well as complex wave load analysis. The different modules are combined in an integrated work bench from which all tasks can be started assuring the integrity and consistency of product model data defined by the user or generated by the programs. The software can be used for any ship type which is covered by the underlying Rules and Regulations. The actual version provides for the calculation of scantlings of longitudinal and transverse structural components according to rule requirements at any longitudinal position. Furthermore a rich set of menu driven procedures exists which allow to apply rules on single or complex structural parts e.g. the overall rudder design. For the integrated analysis two different modules exist:

- "Section Scantlings" for the hull cross section modelling and assessment according to rules
- "Modeller" for the definition of a 3-D model and the creation of finite element meshes.

In the following the first tool is described which can also be used to create input to the "Modeller".

With help of the "Section Scantlings" tool, which is the direct successor of the PILOT software, the longitudinal structural elements are defined in a 2-D view which holds no information on the longitudinal extent of the components. Special menus exist which are to be used for the definition of functional components like shell, deck, inner bottom, girder. The associations between these elements are checked by the program. Symmetry of components to the ship centre plane can be controlled by the user which makes it possible to model almost any structural configuration. Spaces are generated automatically, they result out of the configuration of structural elements taking holes and cutouts into account. Additional data like contents parameter or height of overflow etc. for tanks have to be assigned by the user. The scantlings of piece parts realising functional elements are checked against locally and globally acting loads. The report indicates piece parts not fulfilling the rule requirements which then have to be changed manually by the user in an iterative process. An automatic calculation as part of Poseidon or ShipRight will be included in one of the next version of the program.

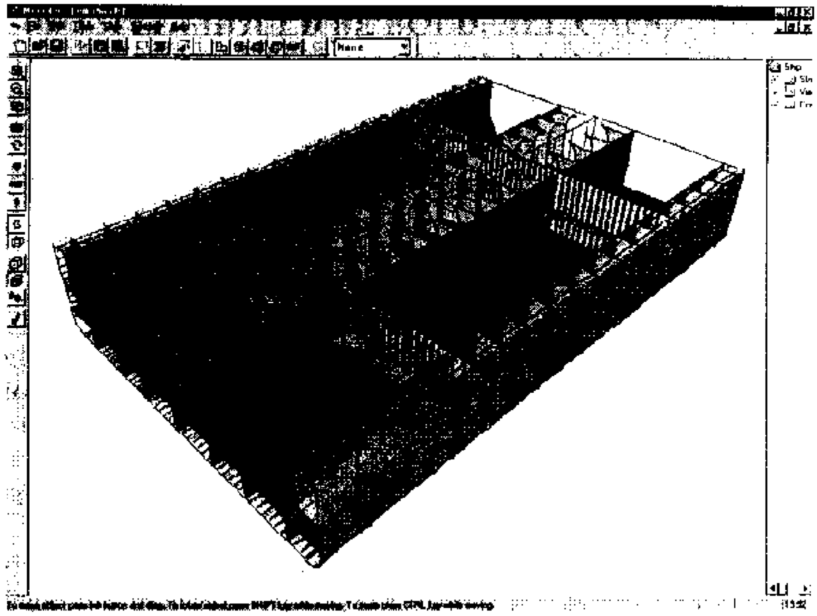

Figure 6. NAUTICUS Hull Modeller: Import of Structural Components using an EMSA Protocol [11]

An additional component may be used to calculate the scantlings of transverse components like web frames or transverse bulkheads.

The integration into the overall ship structure design process can be realised by

- Macros supplied which can be used in NAPA to export a hull form in a DXF-format for input to the modeller component.
- Pre- and post-processor to read and generate ASCII formatted files containing hull cross section definitions in a specific format.
- Interfaces under development to support a data exchange in correspondence of the EMSA business case "Hull Structural Design Approval", see **Figure 6**.

Poseidon (GL)

The actual Poseidon version (1.5) of Germanischer Lloyd can be used for any type of ship (structural configuration), the following principal functions are provided:

- calculation of scantlings according to rules for single plates and stiffeners as well as for hull cross sections including longitudinal and transverse members,
- direct calculations based on generated 3-D structure models. For this, a general purpose finite element solver capable of linear, non-linear and dynamic calculations as well as a pre- and post-processor are part of the standard distribution.

The structure model is specified by hull cross sections. Wizard dialogs help to speed up the definition of specific ship types: tankers, bulk carriers and container ships. Associative and parametric modelling is supported, a distinction between functional and piece part view is made. For each of the primary components (functional elements like deck, shell, bottom, bulkhead, ...) the extent in longitudinal direction can be specified, overriding the default value which gives no limitation. The modelling of shape modifications of structural components in longitudinal direction is to a certain extent supported as the same component can be assigned different shape information at any number of cross sections. A cross section consisting of longitudinally and transversely oriented structural elements defined at a specific longitudinal position can easily be copied to other positions while automatically taking care for modifications e.g. due to the ship hull form or longitudinal elements which are not parallel to the ship centre plane. Symmetry of components to the ship centre plane can be controlled by the user which allows for the modelling of almost any structural configuration. Spaces are generated automatically, they result out of the configuration of structural elements taking holes and cut-outs into account. Additional data like contents parameter or height of overflow etc. for tanks have to be assigned by the user.

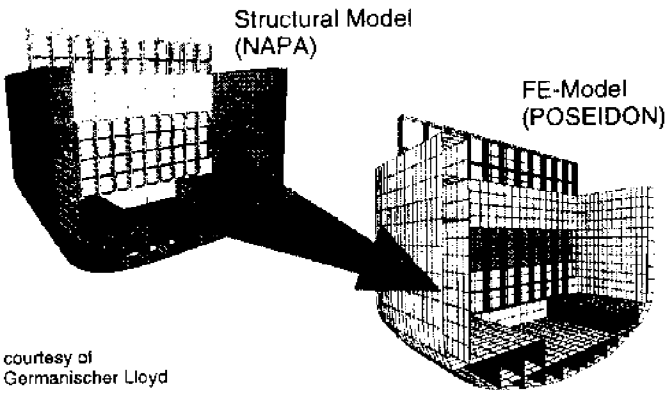

Figure 7. Interfacing NAPA and Poseidon

Scantlings of piece parts making up the hull cross sections are calculated according to rules almost automatically. The user has only to supply those dimensions which are to be taken as constant values in the iterative process, examples are plate thickness of coaming, deck and shear strake of a container ship or the inner bottom thickness in cargo holds of a bulk carrier which might be part of the owner's requirements. The global shear force and bending moment at the longitudinal position under consideration as well as locally acting loads due to a defined tank configuration or deck specification are taken into account in the dimensioning. This functionality allows the program to be used very early in the design process for a reliable estimate of the scantlings of a major part of the hull structure and for the calculation of the weight distribution. The required input is minimal, modifications can be carried out easily due to the associations which are forced to be used in the definition of the structural configuration.

An optimisation of the structural design is part of the program and is controlled by the user. For this, the resulting stress level is indicated for all parts and suggestions are made on how scantlings should be changed which are defined by the user as to be kept constant in the iteration by the program.

A 3-D model is defined implicitly by the set of 2-D cross sections. For the generation of a finite element model this information is used and elements are created automatically taking the user defined maximum values of element size for geometrically defined regions into consideration.

An integration into the design process can be realised by:

- Macros to be used in NAPA to export a hull form in a format suitable to input to Poseidon
- A pre-processor to read in specific ASCII formatted files containing 2-D
- A library with data access functions to directly operate on the system internal persistent data structures
- Interfaces under development to support a data exchange in according to STEP AP 216 con-

formance classes and the EMSA business case "Hull Structural Design Approval"

A close integration is realised with the naval architecture calculation package E4, the system architecture is depicted in **Figure 8**. In this configuration, the structure is modelled with help of the functions supplied by E4. Upon request, defined parts of the model are transformed into the "Poseidon-view" making use of the data access functions library. The rule calculation request starts a new process which communicates back some status messages. After receiving the OK-status, the calculated scantlings are automatically read into the E4 internal data management component where the corresponding attributes of plate and stiffener objects (thickness, cross section parameter) are assigned the new values. In normal operation, the calculation according to class rules is done automatically in a background job and controlled by the user through the E4 package.

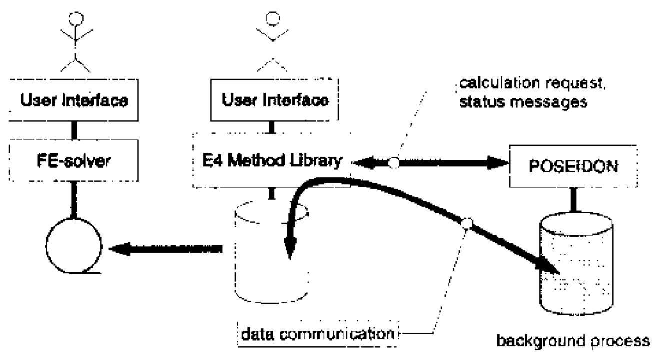

Figure 8. E4–Poseidon Integration: System Architecture

KR-TRAS (KRS)

The KR-TRAS software (actual version 2.0) by the Korean Register of Shipping consists of a set of independent programs for the assessment of different structural components like deck plating, bottom structure or rudder, ... Among these, a program exists which allows for the definition of hull cross sections and the calculation of hull cross sectional data based on a 2-D model. The cross section is defined by plates and stiffeners. A functional description of structural components is not supported and a longitudinal extent of structural components can not be defined. An automatic calculation of scantlings according to rule requirements and global as well as local loads is not available but planed for the next release.

The software distribution includes KR-RULES which is a hypertext version of the KR Rules for Classification of Steel Ships.

ShipRight^IS (LR)

The ShipRight^IS software supplied by Lloyd's Register of Shipping will, in time, supersede all existing programs which are known under LR.PASS. Based on a common database holding a single ship representation used for all types of calculations, different modules are offered in an integrated software system which supports the calculation of scantlings according to the LR rules as well as direct structure analysis of structural components. The software can be used for any type of ship covered by Parts 3 and 4 of the LR rules for steel ships. The actual version (1.3) does not support the calculation of rule scantlings of transverse structural components and of longitudinal components which are outside the 0,4L midship region.

The user is guided through the modelling and calculation process with help of a "road map" which assures that all required data are available for the subsequent tasks to be performed. The structural model is generated by the definition of longitudinal structural components. The fore and aft extent in longitudinal direction has to be specified for which a reference to a frame positions can be made. Furthermore a structure type has to be assigned out of a predefined set. The definition of components is supported by type-specific input parameter. Symmetry of components and spaces with respect to the ship centre plane is assumed, elements crossing or lying in the centre plane are handled correctly. The hull form is to be defined separately using different modules which offer either a cross section or 3-D, parameter driven modelling functionality. The deck is regarded as a specific structural component and has to be defined using an extra function. Associative modelling is supported, a distinction between functional and piece part view is made. Spaces are defined by specifying the bounding structural elements manually. Additional data like contents parameter or height of overflow etc. for tanks are to be assigned.

Scantlings of piece parts making up the hull cross sections are calculated according to rules almost automatically. The user can supply those dimensions which are to be taken as constant values in the iterative process. The global shear force and bending moment at the longitudinal position looked at as well as locally acting loads e.g. due to a defined tank configuration or deck specification are considered in the dimensioning process. This functionality allows the program to be used very early in the design process for a reliable estimate of the scantlings of a major part of the hull. For this, the required input is minimal, modifications can be carried out easily due to the associations which are defined in the modelling of the structural configuration.

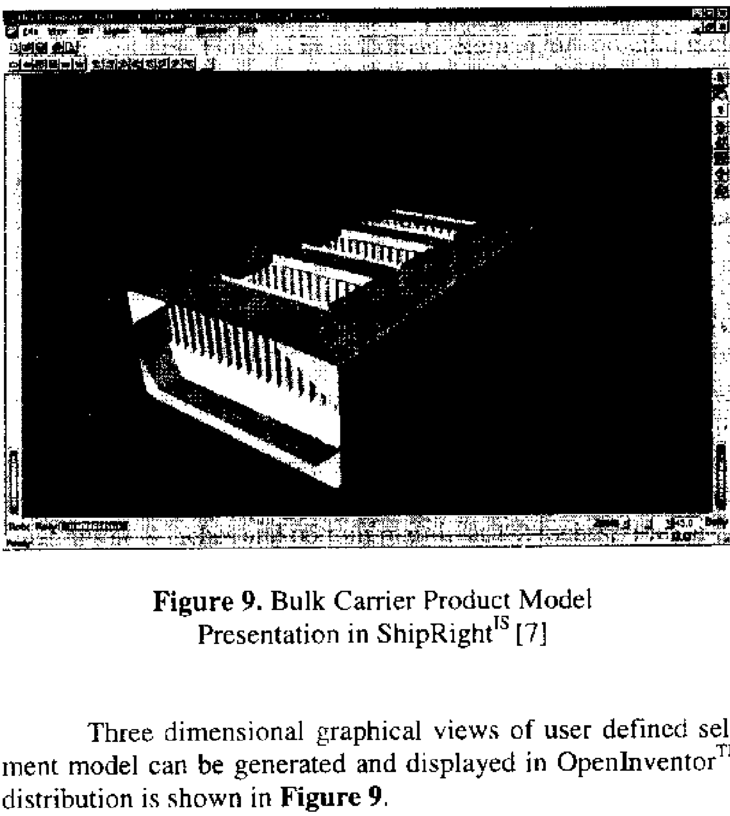

Figure 9. Bulk Carrier Product Model Presentation in ShipRight^{IS} [7]

The 3-D model serves as the basis for the highly automated load case and finite element mesh generation according to the Structural Design Assessment (SDA) procedures which are implemented for tankers and bulk carrier. The generated element size can be controlled by the user specifying different values for different structural components.

Three dimensional graphical views of user defined selections of the ship model or finite element model can be generated and displayed in OpenInventor^{TM}, an example, taken from the software distribution is shown in **Figure 9**.

An integration into the overall design process is realised by

- import of hull form definition from SeaSafe,
- import and export according to different product models defined according to the STEP methodology: ShipRight specific schema, EMSA business case "Hull Structural Design Approval", see [10], an example for data import is shown in [11],
- import and export of hull form definition as offset tables in a specific ASCII format,
- export of structure in VRML format,
- export in a specific format to be used as input to the hull condition monitoring program.

PrimeShip (NKK)

The PrimeShip BOSUN software by ClassNK Nippon Kaiyi Kyokai allows for the calculation of scantlings of general cargo ships, bulk carriers, container ships and tankers according to the

ClassNK rules. The built-in "integrative design" feature is to used for the modelling of hull cross sections at any longitudinal position and the calculation of the corresponding hull cross sectional data. A functional description of structural components which have to chosen out of a predefined set and a separate piece part definition is implemented. Associations between the functional elements are part of the model. The structure is assumed to be symmetrical with respect to the ship centre plane. A longitudinal extent of structural components can not be defined. Only limited functions exist which ease the definition of multiple cross sections at different longitudinal positions. An automatic calculation as part of ShipRight or Poseidon is not included.

The menu driven "independent design" function can be used for the assessment of scantlings of individual structural members.

MAESTRO

Another approach is followed by the MAESTRO software system. As described by Dow et al. [12], the capabilities for a rationally based design of large, thin-walled structures are built on a rapid structural modelling with special functions for an optimised generation of a global ship structure finite element model. This model serves to generate detailed finite element models as necessary. A determination of scantlings according to the rule books is not supported. Due to the realised first principal design concept, a user-defined safety factor, which can be indexed to the requirements of e.g. classification societies is included in the limit state analysis function. The import of an existing preliminary structural design (generated by SHIPSTRUCT of the GODDESS system) is realised by an bilateral data exchange interface, functions to export FE-model data to an external solver like NASTRAN are included. BV's system VeriStar uses MAESTRO for the 3-D structural analysis.

Conclusion

The short overview of tools offered by the classification societies show that:

- A hull cross section 2-D model is used to calculate the scantlings of the longitudinal structural components.
- Very different modelling functions are offered for the structure definition.
- Most of the software distinguishes between a functional and a piece part model of the structure.
- Some tools allow for an automated calculation of scantlings.
- Assessment functions for transverse structural components are in most tools less elaborated than those for longitudinally oriented components.
- Completely different strategies are followed to manage the transition between 2-D and 3-D models.
- All 3-D models include major restrictions with respect to the shape of structural components or compartments.
- Different strategies are offered to automate the generation of finite element meshes for a direct analysis.
- All input has to be given alpha-numerical, graphical functions are limited to the presentation and most of the tools offer only primitive viewing functions.
- The user interface in almost all tolls is inconsistent between different components.
- Vendor specific formats are supported for data import and export. It should be noted that most of the data exchange functions described in this paper with respect to ISO STEP or EMSA protocols refer to results of ongoing research projects and are not commercially available product components.
- All tools are complex software systems which can not be utilised on an ad-hoc basis. The far most important part in the investment is the user training required.
- All programs run under the Window™ operating systems.

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SEAMLESS INTEGRATION OF STRENGTH ASSESSMENT INTO A CAD ENVIRONMENT

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Abstract

The tough competition throughout the maritime world has resulted in a demand to work smarter! Utilising the power of the existing design and production tools in a more integrated manner will be an essential issue for improving productivity and quality.

Essential factors for the designing of more efficient ships and for classification of ships will be the ability to:

- make the design as mature as possible as soon as possible
- integrate designer, manufacturer, and control authority for the product during product evolution.

This can be achieved mainly by the product model technology:

- closing the gap between the layout of the steel structure and its approval
- bridging the gap between the parties involved in the product development
- linking the appropriate rules to the envisaged layout at an early stage

The emerging role of Product Models in an open environment has created a demand for software vendors to expose their product services through a standard Application Programmer Interface (API). For CAE system vendors, important services will be:

Construction Idealizer,

The role of this component is to create structural analysis models according to type of analysis. (Global, Cargo Area, Local) and to derive numerical analysis models. The idealisation of for example geometry can be to disregard all cut-outs and openings in the design.

Analysis Engine,

The role of the Analysis Engine will be to provide services for a wide number of analyses. This Engine will define and implement a suite of interfaces for structural analyses of marine structures in general and of ships in particular. Relevant results from analysis will be part of the product model data and use services from the Product Model.

Class rule Engine,

The role of this component is to ensure that analysis results are accepted by the classification rules.

The paper will illustrate how to transfer a CAD made model into a CAE system, performing the analysis and do the strength assessment according to the class rules.

Background and Motivation

Computer based design and data integration has many facets. Bearing in mind the structural paradox that **you need to guess the ship's scantlings in order to settle the scantlings,** we know that ship design is an iterative process. The principal objective of the requirements defined by computational ship analysis is to provide a framework for the evaluation of the hull structure against defined acceptance criteria based on an extended calculation procedure covering load and structural response analyses. The requirements ensure that the structures comply with the general load and strength criteria.

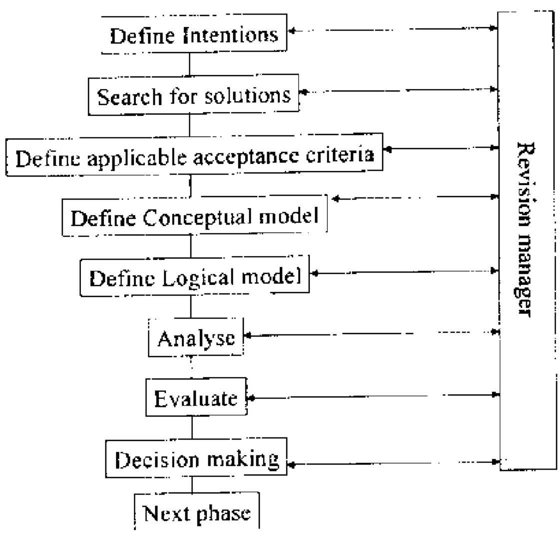

Figure 1 Good revision management is necessary when working with complex designs.

As will be discussed in later sections, conceptual design is influenced by decisions made during the design process. For this reason it is necessary to support the design process with flexible and advanced tools.

However, until now limited use of direct calculations according to first principles have been carried out in ship design. The main obstacles have been poor IT support, together with domain experts not addressing the same master model throughout early design. Particularly, IT solutions have suffered in the area of revision control, constraint management and rule based design (see figure 1 and 2). It is reason to believe that good design applications will appear in the near future.

The nature of conceptual design is to map functional requirements into the emerging solution space and at the same time to keep track of all relations involved. A more precise breakdown structure of the design process could be:

- Layout design or conceptual design
- Scantling design of primary structures
- Production design and design of details

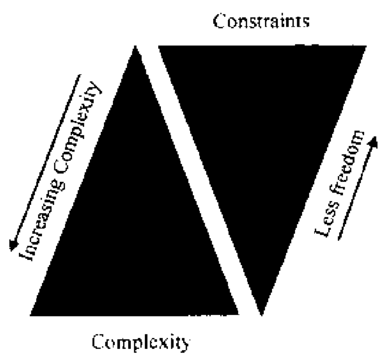

Figure 2 Proper constraint management will ease the revision control

In order to increase the efficiency in the design and strength assessment phase the following factors apply:

- Make the design as mature as possible as soon as possible
- Integrate designer, manufacturer, and control authority during product evolution.

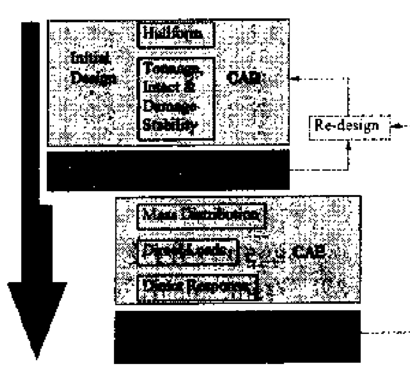

Figure 3 Integration of CAD & CAE in the same overall workflow.

The emerging open modelling environment accommodates integration of third party model structures; the imported data are instantly available for further work within the CAE environment. The Programmers Interface (API) allows users to extract conceptual data for further use within its own workflow by efficient tools for each separate task in the strength assessment process.

Why Product Models

The product model technology enables us to unify the handling of information and the flow of information in a complex design, engineering, production, and operation environment. In this environment, the product model acts as an information carrier that maintains the representation of the product throughout the life cycle. Different aspects of the model can be accessed through abstract views of the model and changes in views can be propagated to the product model and thus to all relevant views of the model.

State of the art today

Today, engineers do not distinguish between the structural models and the analysis models and are too concerned about "non-engineering matters" such as disk space, computational efficiency, geometry to be meshed, loads to be applied, etc.

Vision

- To enable the engineer to concentrate on structural engineering and to use his knowledge and skill to do engineering rather than to focus on how the analysis model is created and represented.
- We see it as a great advantage that the engineer is concerned only with the structural and constraint definitions, and has at his hands a system that, given a selected analysis model, provides him with accurate, reliable and representative predictions of the response after being fed with structural and load details and definitions.
- Accurate transfer of information between engineering models and analysis models to provide valid mappings both ways. We want to transfer geometry, kinematics, equilibrium states, material to the analysis engine and after analysis to receive the predictions as stress, strains and sectional forces in order to do proper strength assessments.

What

In the design process the intentions behind a design are transformed to a design model under constraints and rules. The design model will be subjected to engineering analyses in order to assess its ability to meet the requirements stated in the intention. I.e. we will need to do a capability analysis in terms of general strength assessment.

One of the key steps in an engineering analysis is the idealization process. The aim of this process is to transform the intentions (under constraints and rules) to engineering models describing them in the language of structural engineering. The models we use are a structural model and a general constraints, boundary condition and load model which we call a constraints model. The idea is that any business intention, constraint or rule that is known and defined in the design model should be built into the engineering model in terms of structural constraints and requirements. And likewise, that any non structural intention, constraint or rule (means that it is not a part of the structure itself but affects and disturbs the structure) is built into the constraints model. These constraints are typically environmental loads, equipment loads, etc. that define and provide disturbances and constraints to the behaviour of the structure. It is assumed that rule loads, gravitational loads and any other physical constraint that may be derived from the product model by default is transferred to the constraints model. We note that structural boundary conditions often need to be applied to regularize the problem if the analysis method is not able to handle singular problems.

What we do is thus an idealization from a design model to an engineering model that has been embedded with engineering knowledge in order to comply with all the intentions, constraints and rules that have been set forth. The design model is assumed to contain the complete domain. We note that we do not foresee that this process will ever be fully automated, but rather be semi-automated with adequate support to ease the logistics for the engineer. The idealization may be viewed as a sequence of transformations where we record each step in order to provide a 'way back' from the engineering model to the design model. Such transformation mechanisms enable us to transfer changes in the design back to the design model in a language understood by the designers.

We develop an analysis and modelling framework in order to support the ideas briefly introduced above. In such a framework we need preprocessors, post processors and general analysis components to do the strength assessment. This leads to the next step in our analysis and modelling framework, the creation of analysis models. In this context an analysis model is a numerical discretization of the engineering problem, for instance by means of finite elements. The creation of numerical models is similar to the process we use to create the engineering model and is done by a sequence of transformations. The main difference is that while the first sequence is semi-automated, this process is automated and we facilitate means for the engineer to tailormake the discretrization to serve specific purposes. Like the former idealization process we ensure a 'way back' from the numerical model to the engineering model. We use the standard Sesam suite of analysis software to perform the basic tasks required in the analysis process, see ref [1]. Since we have two engineering models we need to do a merge when we create the numerical model. This process is non-trivial but enables us to tailor the discretization to serve specific purposes, see also the short discussion on adaptive finite-element analyses in the next paragraph.

Important methods and concepts in the analysis and modelling framework are model adaptivity and adaptive finite-element analyses. Model adaptivity, see ref [2], is a technique we use to ensure that the numerical models are capable of representing complex physical behaviour in an adequate way in order to provide good predictions of the response. We may start in a reduced space, say 2D, and enforce kinematic constraints, for instance from Kirchhoff hypothesis. If this reduced space cannot represent what we want to analyse, we transform the model to full 3D theory in the critical areas. Adaptive finite-element analysis is another technique we use to reduce the actual numerical errors in the computations, see ref [3]. The main concern here is to tailor the discretization to the constraint situation and enable an adaptive refinement of the discretization until it provides a response prediction with an error estimate that meets the requirements. The procedure is then a standard implementation of adaptive FE analysis. One problem with this strategy is that it works well only with simple elements. There are considerable problems to develop good error estimators for more complex finite-element formulations.

How

In general, today's ship design (CAD) and engineering (CAE) applications are autonomous systems with limited or no collaboration/interoperability, a situation which is illustrated to the left in Figure 4. Great effort is spent on various initiatives like ISO/STEP and others aiming at closing the gap by developing standards for product data exchange. So far very few shipbuilding applications in the CAD/CAE area have implemented commercial support for these standards and implementation in the shipbuilding industry is not apparent. One reason for this might be the fact that these approaches have several drawbacks with respect to model updates, translation from one representation/ implementation to another etc.

A solution that has been proposed is to move from data exchange to data sharing. The main problem with this approach is that representation/implementation of the model is often very different for the different areas of concern. CAD models are often rich in details and targeted at manufacturing and production systems while CAE models are often less rich in details and targeted at structural strength assessment analyses. The different areas of concern often require different approaches with respect to model representation and implementation

In the years of component based applications and open systems architecture, a new approach to this problem is to design architectures for collaborating and interoperable systems. This paper describes how key features of a collaborating CAD – CAE system is implemented in a COM based environment. The goal is illustrated by CAD and CAE applications using services and data from each other through well defined interfaces but leaving the representation and implementation details at the serving application as seen in the right hand side of Figure 4. The rationale behind this approach is to separate areas of expertise. CAD systems are probably the best implementations for design models, while CAE systems are probably the best implementations for engineering models.

Figure 4

Even though CAD and CAE systems have different areas of concern they often have common features and model properties (for example geometry). For those areas model relationships and open interfaces are extremely important.

Principles for collaborating components

There are two different philosophies for the information flow between a client (which is a user of a service) and a service engine (both of which are components). The information source is a common repository for both Design and Analysis, and the Analysis services will need access to the relevant subset for computation. This subset can be made available in two ways:

- **Push**: The client invoking a service loads the data into the service engine.
- **Pull**: The service engine retrieves what is needed to execute the service.

In general, pull is preferred for the transfer of geometry and results. The reason is that the *user of the data* (component) knows how to receive the data – it is difficult for a client to know what is the most efficient way of transferring data to the other component. This implies:

- For the geometry a service engine needs as input, the service engine will be told where to get access to it, and the service engine will retrieve what it needs.
- For complex results, the client will be told where to retrieve it.

This implies the following actions when a service is invoked by a client:

- The client configures/sets up the service (push)
- The client informs the service engine where to retrieve the data (push)
- The service engine retrieves the data (pull)
- The service engine does the work, informs the client that it has finished, and communicates how the results can be retrieved. (push from the perspective of the service engine)
- The client retrieves the results (pull)

Data passed between components are often transformed. It is the responsibility of the components that do such transformations to maintain relationship between the original and transformed state. This is necessary in order to communicate changes based on analysis to the CAD-system.

Managing model relationships

As mentioned above, the area of concern for CAD and CAE is different. CAD models are rich in details and targeted for manufacturing and production. On the other hand, CAE models are less rich in details and targeted towards efficient, robust and reliable numerical analysis. An examples that illustrates the problem is a knuckle in the double bottom shown in Figure 5. In a CAD system the girder will be offset some millimetres from the knuckle due to production related welding rules. while a CAE system for a global analysis case would "snap" it to the knuckle point in order to reduce mesh complexity. In this "structural idealization" transformation the topology in the analysis model differs from the topology in the design model. This relationship has to be maintained. In order to do this a separate relationship object is implemented to maintain the semantics of the relationship. This relationship must be maintained across system borders and implies some requirements to which interfaces the CAD and CAE applications must support on the model level in order to inter-operate and collaborate efficiently. A relationship interface must be supported and it must act as an event source for the relationship semantic object so that this object is able to maintain the semantics of the relationship in the event of changes relevant for the relationship.

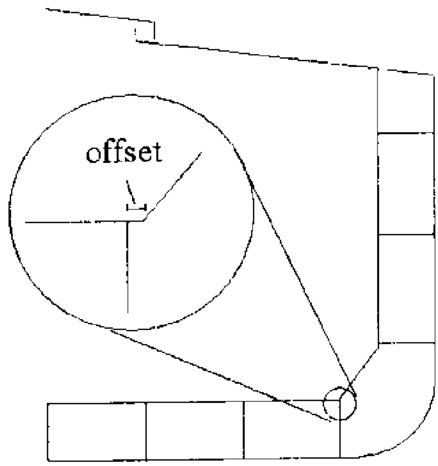

Figure 5 A knuckle in a double bottom.

Overall architecture

As illustrated in Figure 6, end users (designers / engineers) interact with an application via tools integrated in the desktop. Two major tools (each composed from smaller components) in open solutions are:

- CADTool – a (new) suite of software services for General Ship Design supporting the use of shipbuilding design and manufacturing concepts.
- CAETool – a (new) suite of software services supporting the use of engineering concepts with main emphasis on FEA and rule-based analyses.

The users of the system are both Designers and Engineers who has different scope of work related to the product:

- Designers,

  Establish the design model which will form the basis for the engineering process and update the design model based on feedback from the engineering process.

- Engineers,

  Will focus on construction and structural aspects of the model based on the work from the design process. The results from engineering processes will be feedback to the design process.

The Designer and the Engineer interact with open solutions via a Desktop, which must be configurable to the specific needs of the different types of users. In the descriptions below, the Desktop is not further discussed, since it is the CADTool and CAETool the user interacts with.

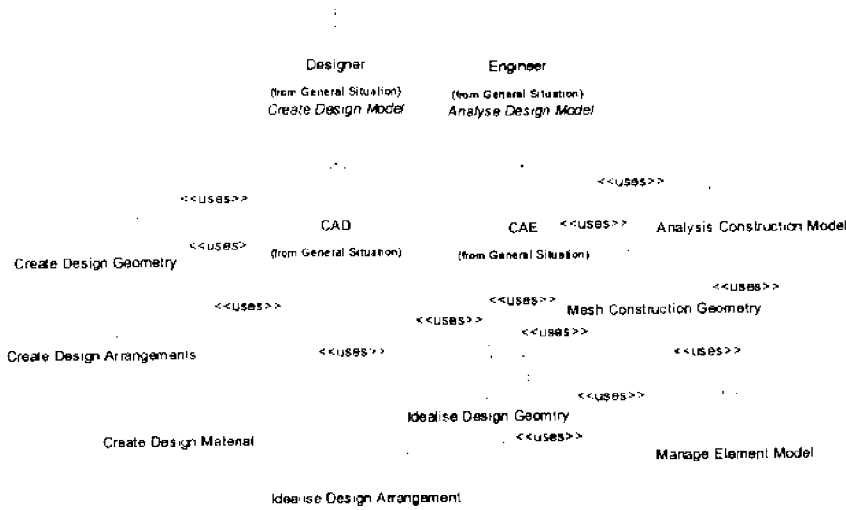

Figure 6 End users and main components

Important components used to build the applications are:

- Workflow,

  The role of the workflow engine is to provide services for defining and managing the work process related to ship design, analysis and production.

- Product Model Engine,

  The role of the Product Model Engine is to provide services regarding product model data and product modelling services through a standard set of interface suites. Important services will be associativity, versioning and configuration management, persistence etc. This engine will to a large extent be based on other services like geometry, constraint management, concepts etc provided by other engines.

The services and engines described above should be based on open solutions. In addition, frameworks for Finite Element Analysis and classification rules will be available. The focus of this document is on Finite Element Analysis, but the architectural goal is to enable other types of analyses.

Important components in the Analysis framework will be:

- Geometry Engine,

The role of the geometry engine is through a standard set of interface suites to provide geometry and topology services for modelling. An important interface suite for this engine is *OLE for Design and Modelling*.

- Constraint Engine,

The role of the constraint engine is to provide services for defining and managing constraints services through a standard set of interface suites. These constraints will be design and modelling constraints, yard manufacturing constraints, but also other constraints such as classification rules and constraints related to meshing of the different structural elements.

- Concept Engine,

The role of the concept engine is to provide services for ship concepts for hull form, arrangements, structural elements, i.e. both Design Concepts and Engineering Concepts as defined in chapter 2.1.
It is important that the interface suites defined for this engine ("*OLE for Ships*") are open and extendable to enable specialised concept information for the different application areas such as design manufacturing and construction analysis.

- Equipment Engine,

The role of the equipment engine is to provide services for equipment.

- Part Library,

The role of part library is to provide services for re-usable building blocks.

- Analysis Engine,

The role of the Analysis Engine is to provide services for a wide number of analyses. It will define and implement a suite of interfaces for analysis of marine structures in general and of ship structures in particular. Relevant results from analysis will be embedded with the product model data and use services from the Product Model Engine.

- Rules Engine,

The role of this component is to ensure that analyses are based on classification rules.

- Structure Idealizer,

The role of this component is to create structural analyses models according to type of analyses, (Global, Cargo Area, Local) and to derive numerical analysis models. The idealisation of for example geometry can be to disregard all cut-outs and openings in the design. Idealize according to idealization level.

- Loads Idealizer,

The role of this component is to make simplifications and associate loads on the structure. The loads handled shall be both static loads such as rule loads and equipment loads and dynamic loads from sea-pressure.

- Mesh Engine,

The role of this component is to establish the finite-element mesh for the given analysis type and mesh parameters.

- Element Engine,

The role of the element manager is, upon request from mesh engine and algorithm engine, to provide elemental matrices and vectors. The elemental matrices are typically stiffness, mass, and damping, and vectors are loads and forces. It must be possible to request matrix and vector subsets, such as diagonal of elemental mass matrix etc.

- Algorithm Engine,

The role of the Algorithm Engine is to provide linear, non-linear and Stochastic solution algorithms.

Summary

We have given an overview of the seamless integration between CAD/CAM and CAE enabled by the use of emerging product model technology and component based software solutions.

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A STUDY ON THE METHODOLOGY AND PROCEDURE FOR SOLID MODEL BASED SHIP STRUCTURE DESIGN AND PRODUCT MODELING

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Abstract

The aim of this study is to develop a ship product model through which a concurrent engineering concept can be realized. The product model can be built on the 3D CAD system having parametric design concept and maintaining database. The required basic functions of CAD system for product modeling are as follows.

(1) Based on a solid model
(2) Supports non-manifold model
(3) Parametric design modeler

The ship product model concept was introduced and developed in this study to enhance the CAD performance that maximizes the efficiency of the design information flow and applications. Two application fields are focused upon: first, the initial and detail structural design and second, the extraction of production engineering information for Computer-Aided Process Planning (CAPP).

A general 3D based solid CAD system was used as a modeling tool. Two modeling methods and simplified modeling concepts were suggested in this study, namely user defined application programs and parametric macros for primary structural members. Two modeling procedures were investigated: unit and ring structure concepts. The unit concept is the modeling of major ship structure parts such as decks, transverse and longitudinal bulkheads, as individual items. The ring structure is that part of the ship structure sliced at two different cross sections along the longitudinal direction of the ship. In the simplified modeling concept, some symbolized objects were used to develop a product model, easily and rapidly. These were automatically converted into solid objects. To verify these modeling concepts and procedures, a typical Very Large Crude-Oil Carrier (VLCC) was modeled and tested.

Introduction

Manufacturing industries have a strong need to exchange production information effectively among design, process planning, scheduling, and production activities in order to increase productivity and shorten production time. A Computer-Integrated Manufacturing (CIM) system can support this requirement. The core technologies in a CIM system are a product model and concurrent engineering based on a database.

Normally, ship design and production planning are carried out in parallel, which in turn, requires efficient production information flow and databases. The detailing of information is a gradual process as the design progresses through the various stages such as initial design, detail design, process planning, and production design. To support the environment of shipbuilding processes, a product model was introduced. The ship product model can be defined as a computer information model that enables information exchange between application systems from contract to delivery. The basic product model information is created by and based on the CAD system.

to delivery. The basic product model information is created by and based on the CAD system. Product models must have capabilities to control the flow of information[1,2,3]. So, the model requires powerful database and database management systems to store and manage the information.

Several research activities have helped to establish the concept of a product model and CIM system in shipbuilding. Representative ones are the development of CIMS Pilot Model[4,5,6], CIMS Frame Model [7,8] in Japan, and CSDP in Korea[1].

In this study, a ship structural design and modeling system was developed based on the product model concept. Ship structural design and modeling work was done by referencing hull and subdivision models. The designed structural information is converted to the CAD model and becomes the start point of ship structural product modeling. In other words, the product model receives required information from the design system. This study intensively tested the automatic creation of structure model from the results of the design system.

From a modeling point of view, ship structures consist of two parts. One is plate element and the other is stiffener element. These items are standard ones to build modeling libraries and the database. In addition, various parametric macros such as for web frames, stringers, slot holes, and collar plates are needed to increase the productivity of ship structural modeling. These libraries and macros were developed, tested, and evaluated through a real VLCC product model design. It was realized that the modeling procedure was very important for improving the performance and usability of the modeling results.

One of the main purposes of product modeling is public use and maintenance of production information between the various working groups. With current workflow procedures, the design data is distributed to the next design stage or production fields in the form of drawings. Users wanting information have to extract the data from drawings. This paper shows how to use the product model created at initial structure design stage in the subsequent detail, process planning, and analysis stages.

Design and Modeling System

1. Hull and Subdivision Modeling

The basic information for ship structure design is the hull form and the subdivision plan provided by an initial design system. At the structure modeling stage, the plate elements use the surfaces stored in the database that were fed in from the initial design system. When defining the major surfaces like bulkheads, these are referenced to the hull form. An example of hull form and major surfaces is shown in Figure 1. These surfaces are stored in the database for later use in the following stages.

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[8] Ship and Ocean Foundation, Research Report on the Development of CIMS FRAME MODEL, 1994.

2. *Structure Modeling*

There are several ways to make a structural model. To increase modeling efficiency, properly optimized modeling methods have to be adapted for each structural group. In this study, a unique programming language was employed for modeling, which provides user-friendly environments for developing user application programs and CAD functions. This method was particularly useful when modeling longitudinal structures. On the other hand the parametric macro library is a good solution for modeling the transverse structures. To improve the model performance, two modeling procedures were considered. They are unit and ring concepts. The ISDP[9,10] CAD system developed by Intergraph Corporation as a shipbuilding solution was used to verify these concepts.

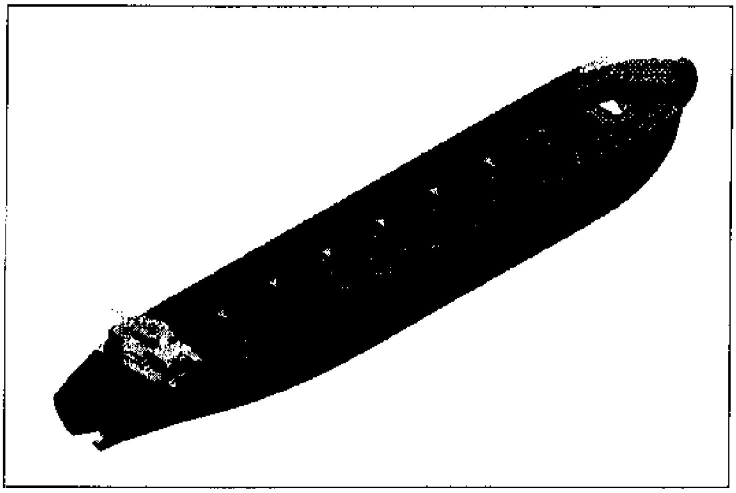

Figure 1. The results of hull and subdivision modeling

2.1 Modeling by User-Oriented Application Program

Several user-oriented application programs and commands were developed using Application Programming Interface (API) Parametric Programming Language (PPL), supplied by the CAD vendor.[11] The programmed CAD functions read model data from the database, generate initial structure elements in the modeling environment, and then modify each element to be an exact representation.

Many of the longitudinal members in the hold section can be automatically placed on the longitudinal major surfaces with the user-defined programs. Plate modeling requires base surfaces and plate attribution information. The attribute data include plate thickness, material properties, plate size, and location. The modeling procedure can be divided into three steps as follows:

1) Place the representative plate on each major surface that references from the previously defined hull and subdivision design model.
2) Split the plate. In this step, the system obtains the split position from the structure design system or process planning system stored in the database.
3) Modify the plates with the exact thickness and material data at each location. To model stiffeners, the system needs its location and attribute information. The typical stiffener attribute data are sectional shape, material, size, and location of the stiffener.

This modeling concept was applied to the VLCC and tested. Figure 2 shows the result of

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[9] Intergraph, I/VDS Reference Manual, 1994.

[10] Intergraph, I/STRUCT Reference Manual, 1994.

[11] Intergraph, Parametric Programming Language (PPL) Reference Manual, 1994.

structure ring modeling. It was found that when applying this modeling method for initial structure design, the product model could be easily built and handled with great accuracy. The process planning and detail design work can start at an earlier design stage and progress quickly.

2.2 Modeling With Parametric Macros

Transverse structural members have a similar shape. Therefore, they can be repeatedly placed along the longitudinal direction of ship. Many of the ship structural members can be modeled efficiently with parametric design concepts. A parametric macro is a library that consists of topology and parameter information. The following are typical parametric macros used in this process:

(1) Transverse Web Frame

The transverse web frame is placed at every frame position except the transverse bulkhead locations. This web frame can be grouped by types depending on location, shape, and topology. Major input variables to place the transverse web frame macros are position, boundary elements, and shape parameters of the web frame.

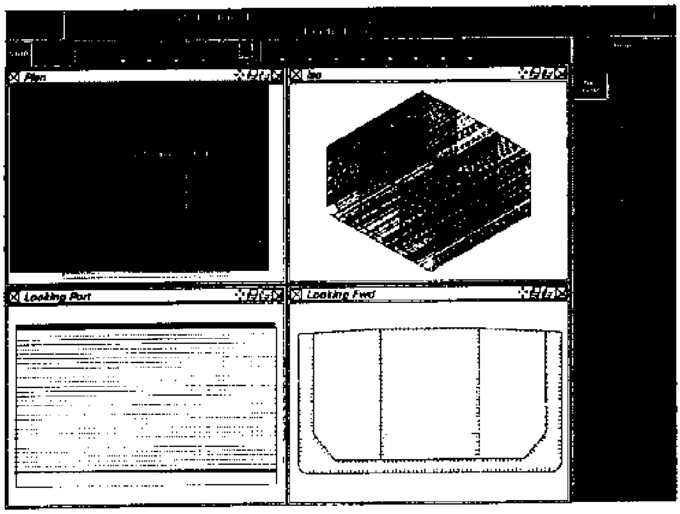

Figure 2. Results of automatic midship modeling using user-oriented programs

(2) Stringer

This element supports transverse bulkheads. It has a complicated shape, so the parametric macro library will be an efficient method for modeling it. When placing the stringer macros, major input variables for boundary elements and shape parameters are positioned.

(3) Slot Hole and Collar Plate

Modeling of slot holes and collar plates becomes important at the detail structure design stage. To develop these macros, the modeler must support the parametric design concept. Major input data for placing these macros are plate, beam, and type of slot holes. In addition, the detail structures like bracket, stiffener, and opening can be efficiently modeled and partially automated with appropriate macros. In the study, more than 150 macros were developed for several types of ships. Figure 3 shows an example of typical parametric macros developed for modeling the VLCC and bulk carrier.

2.3 Modeling Procedure

To define optimum modeling procedures, investigations on modeling efficiency, usability, and reliability are essential. From these points, two modeling concepts focused on improving the modeling performance. They are the unit modeling and structure ring-modeling concepts. A main purpose of product modeling is the reuse and sharing of information by various working groups. Therefore, the reusability of modeling information also has to be deeply investigated.

(1) Modeling Method Based on Unit Concept

In this model, the number of structure design files is same as the number of major surfaces defined in hull and subdivision design files. In other words, all major surfaces have their own separate structure design file. Hence, this method is inefficient, particularly from a usability point of view because the size of design file becomes too large to handle it.

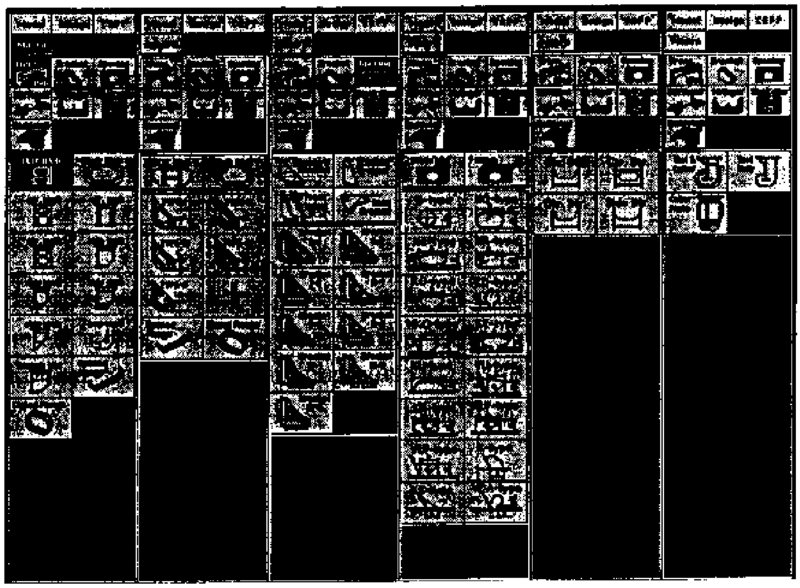

Figure 3. Example of parametric macros for the VLCC and bulk carrier

The typical structure units of VLCC are deck, shell, port and starboard longitudinal bulkheads, inner bottom, transverse bulkhead, and web frame. Figure 4 shows the modeling flow in the unit modeling method. This procedure is very convenient, especially at the initial design stage. As the design progresses, the amount of information rapidly increases. The size of the unit model becomes very large in detail. Therefore, it is difficult to control the unit model at the detail design and process planning stages. The ring structure model was proposed to solve this problem.

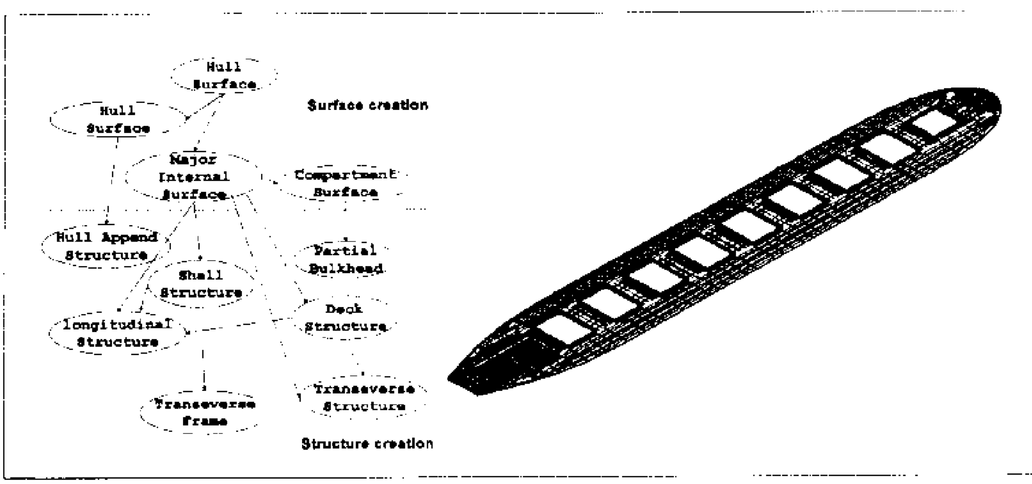

Figure 4. Modeling flow in the unit met modeling method

(2) Modeling Method Based on Structure Ring

Generally, the block division processes proceed with initial structure design at the same time. It means that the basic ship construction plan should be decided at very early stage. Furthermore, the unit concept is not suitable to support this process. Hence, a new modeling procedure, so called structure ring, was proposed to support concurrent engineering in the initial stages. Ring means a sliced section of a ship. The size of structure ring model is much smaller than that of the unit model. So it is efficient to control the model even at the detail design level. Figure 5 shows a modeling flow diagram of this concept.

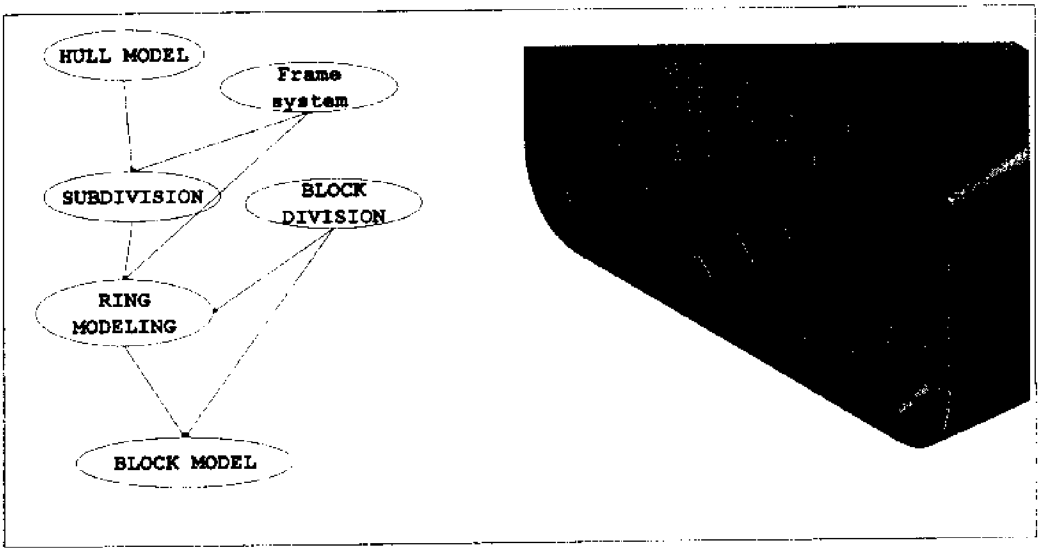

Figure 5. Modeling procedure for ring structure

The basic concept is the split of major surfaces defined by hull and subdivision systems at longitudinal block division locations. Then the structure elements are modeled on the split surfaces. The model created by this procedure has merits on detail structure design and process planning. However, there are considerable disadvantages on the modification of design, integration, and automation of the structural design system. These modeling techniques were applied to the VLCC to validate their effectiveness. Figure 6 is a typical ring structure model of a VLCC at engine room part. This ring model can be created easily using the automatic modeling system and parametric macro libraries.

3. Application of Modeling Results

The main purpose of product modeling is to use it efficiently at various domains. This study focused on three engineering fields: detail structure design, process planning, and CAE model generation.

3.1 Model for Detail Design

In present design processes, most of initial design information is transferred to the detail design parts by key plan drawings. This means that design information is to be concretely remodeled at the detail design stage. Under the integrated environment based on the product model, the initial design results can be transferred to detail design parts through the product model. The detail design and production information can be generated from the model. A series of tests for 2D drawing extraction from the 3D model was executed in this study for the structures of deck and transverse bulkhead of VLCC.

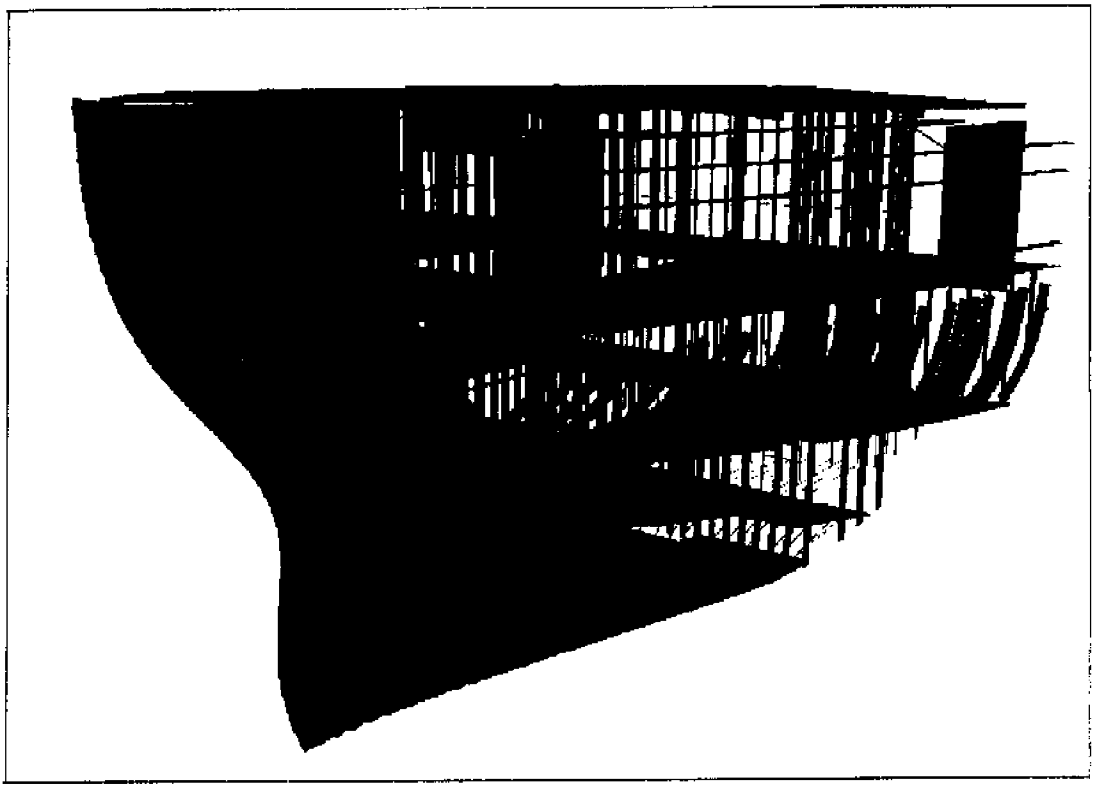

Figure 6. Structural modeling of engine room part

3.2 Model for Process Planning

In a product modeling system, design information stored in a common database can be promptly used by process planning engineers. Conversely, the process planning information is easily transferred to design groups. Figure 7 shows examples of production planning information extracted from the product model. The system provides information on plates, stiffeners, and joints. The process planning works such as block division drawings and lifting plans are time consuming and repetitive jobs. These drawings can be generated automatically from the product model. In addition, the model information can be linked to and used for production scheduling systems.

3.3 Generation of CAE Models

The CAE models for finite element analyses and computational fluid dynamics can be extracted from the product model. In this study, various CAE models were developed from the hull and subdivision surface models and structural solid models.

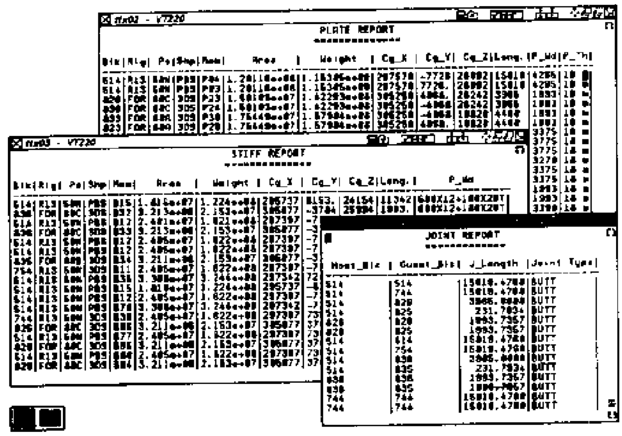

Figure 7. Report for plates, stiffeners, and joint information

4. Simplified Modeling Concept

One of the main purposes of product modeling is to extract manufacturing information. A commercial ship design process consists of marketing design, initial design, detail design, and production design. Each design stage must produce production information in a timely and efficient manner. At the marketing and initial design stages, due to special design cycle circumstances, structural members are defined and modified several times in a short period. The "simplified modeling concept" (shown in Figure 8) was introduced in this study to rapidly and easily model structural members.

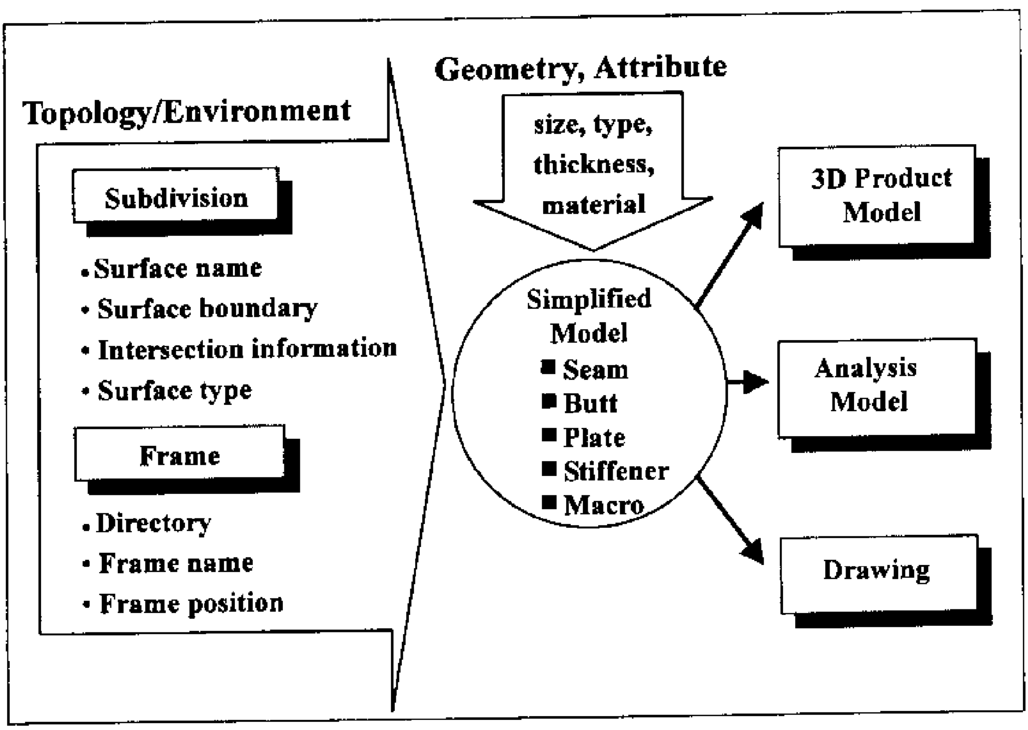

Figure 8. The environment and procedure of the simplified modeling concept

The simplified model developed through the procedure of Figure 8 can be converted into structural drawings, solid models, and finite element analysis (FEA) models as required from the "simplified objects" defined at early design stage. The simplified objects are composed of geometry of 2D wireframes, attributes of members, symbols for drawing, and information for converting to 3D, etc. as shown in Figure 9.

4.1 Modeling Test Using the Simplified Concept

In this study, the deck structure model was built to verify the simplified modeling concept as shown in Figure 10.

OBJECT	Topology	Wireframe or expression
	Geometry	Object boundary in wireframe type
	Attributes	Structure attribute & user attribute
	Symbol	Symbol definition for drawing

Figure 9. Types of simplified objects

From the test, it was understood that the simplified modeling concept:

1) Provides a user-friendly environment for 3D modeling which is similar to 2D drawing work.
2) Can be easily converted into different output formats such as basic drawings, FEA models, and detail solid models.
3) Retains parametric and associative relations between the members.
4) Is easy to modify and verify design parameters.
5) Is easy to interface with other applications.

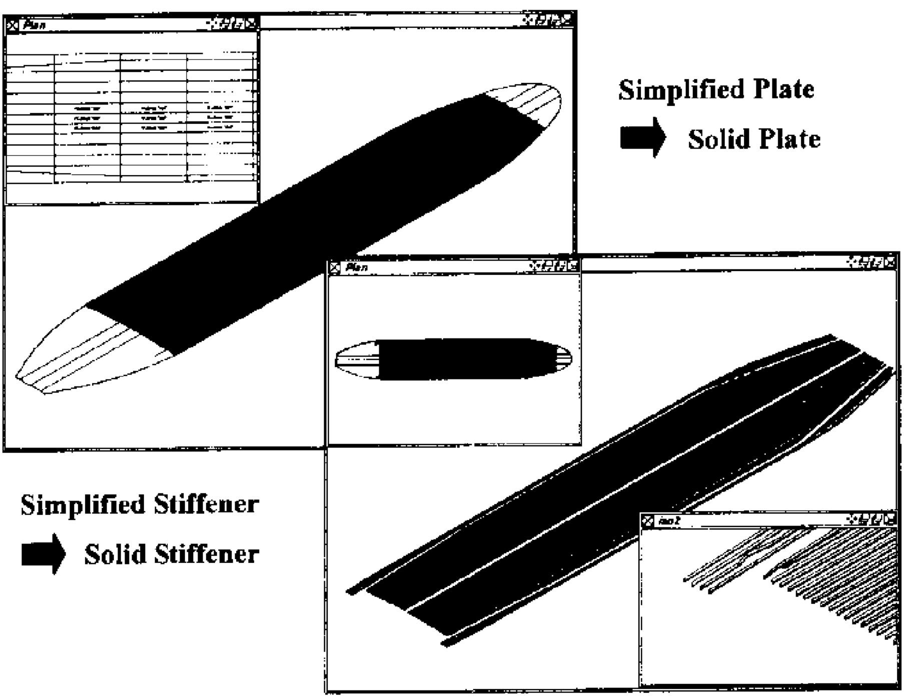

Figure 10. The results of simplified modeling

4.2 Comparison Between Solid Object and Simplified Object

Since the 1980s, with the dramatic improvement of computer performance, many people have tried to represent real products in computer fields such as CAD, simulation, and virtual reality. In shipbuilding, as a part of these efforts, it has been attempted to build a solid based ship product model. There are some merits and demerits of solid modeling as follows:

1) Merits of solid models
   - Gives a correct understanding of the real shape
   - Represents interference information
   - Represents manufacturing information
2) Demerits of solid models
   - Increases modeling time
   - Increases amount of modeling information
   - Degrades system performance

Solid modeling is good for its purpose; but concerning the issue of efficiency, it still has limitations and problems due to the huge amount of product information for a ship. So we recommend a mixed model which has both solid objects and simplified objects. Of course, simplified objects should have 3D information in order to automatically convert it into solid objects when required. Figure 11 shows the mix-rates recommended for each design stage.

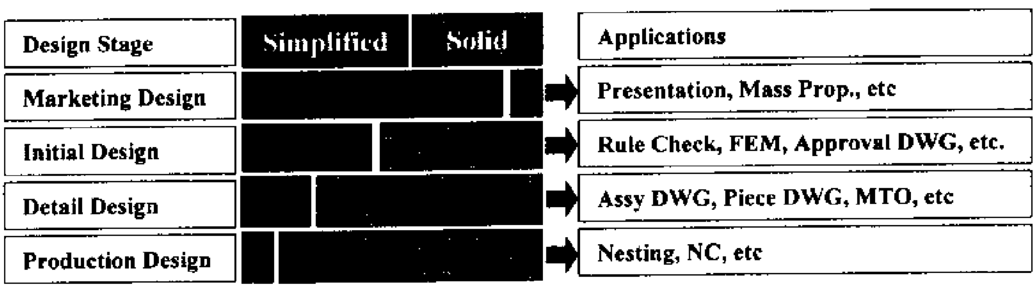

Figure 11. Mix rates of solid objects and simplified objects

Discussions and Conclusions

This study was performed to develop a ship product model through which concurrent engineering can be realized. Efforts were made to suggest an efficient and optimum modeling procedure in initial design stage. The product model was tested and validated by applying the suggested modeling methods to the typical VLCC design. The results of this study are as follows:

(1) For realizing concurrent engineering in shipbuilding, product modeling will be the best solution.

(2) User-oriented CAD functions and commands like parametric macro libraries are essential to build a ship modeling system. They provide user-friendly modeling environments that facilitate easy and convenient modeling.

(3) When designing the modeling method and procedures, both the modeling efficiency and model usability should be considered.

(4) A powerful database and DBMS is required for successful ship modeling. This ensures efficient information flow and common use of design data between various working groups. In addition, a CAD modeler supporting non-manifold, parametric, and solid modeling system is recommended to develop a next-generation shipbuilding CAD system.
(5) The unit and ring modeling techniques were suggested for initial and detail structure design processes, respectively.
(6) Production planning information was successfully drawn from the VLCC product model defined at initial design stage.
(7) A simplified modeling concept was suggested to solve the problems of full solid object modeling at the initial design and process planning stages.

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POTENTIAL BENEFITS DERIVED FROM INTEGRATION OF CONCEPTUAL DESIGN TOOLS FOR 3-D MODELING AND SIMULATION

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Abstract

The inherent shipbuilding and design benefits afforded via 3-D Modeling and Simulation (M&S) capabilities are well known. What is important for the designer and shipbuilder to consider regarding M&S is the difference, and the value added, among 3-D visualization and 3-D physics-based virtual prototype modeling capabilities. Depending on the specific 3-D M&S capability used, the potential for cost savings during life cycle phases such as production or overhaul may be considerable.

This paper will propose a reliable method of producing a 3-D, physics-based kinematics virtual prototype model while reducing modeling, by using Commercial Off The Shelf (COTS) software. Models used for visualization generally provide just that, visualization. Accordingly, they provide little analytical ship design benefit. This paper will define the methodology of creating a 3-D, physics-based kinematics virtual prototype model suitable for performing tasks such as design and overhaul evaluations. A detailed description of the cycle involved in porting data to and from software packages will be provided. The paper will additionally evaluate a modeling capability to provide data back to an analytical package. A description of current capabilities and links to legacy programs will also be assessed.

Though cost savings are not quantifiable at this time, they are inherent in this approach. The approach focused toward cost avoidance through reduction of engineering changes. Currently 10% of acquisition costs for a lead ship and 5% for follow ships are earmarked for changes. An anticipated reduction of 20% of the fund earmarked for changes represents significant program savings.

The feasibility of integrating ASSET, HFDS, and NAVSEA's Seakeeping simulation into newer models will additionally receive technical consideration as will the use of existing models developed for other ship programs. Exploration of data standards in formats suitable for the manufacturing and government communities will be a key aspect of this paper. Building from recent discussions at the UK/US Design Computing Working Group 1997, this paper will reflect related debate surrounding the integration of conceptual design tools for 3-D M&S.

Nomenclature

A list of acronyms and abbreviations used in this paper follows:

.gaf	——	Graphic ASCII file format(CV)
.stl	——	Stereo lithography file format
3-D M&S	——	3-Dimensional Modeling & Simulation
AMR	——	Auxiliary Machinery Room
ASSET	——	Advanced Surface Ship Evaluation Tool
ATIS	——	Advanced Technical Information Support System
CAD	——	Computer Aided Design

COTS	——	Commercial Off The Shelf
DCWG	——	Design Computing Working Group
GODDESS©	——	Government Defense Design for Ships and Submarines
HFDS	——	Hull Form Definition System
HSI	——	Human Systems Integration
HVAC	——	Heating Ventilation and Air Conditioning
SET	——	Shipyard Engineering Team
VCG	——	Vertical Center of Gravity
VTC	——	Video Teal Conference

Introduction

The U.S. Navy has long been responsible for the design of Naval Warships; however, with changing times, this responsibility is shifting to the shipbuilders. It is this paradigm shift that has become the impetus for the development of the process and suite of programs described in this paper. The premise for these programs is simple: Use one model all the way through the design process. Elimination of the need to model multiple times during the design process will in the end save millions of dollars. These saved dollars can then be better directed toward improving the war-fighting capability of the ship. The goal of this one-model process is to provide the shipbuilder and designer with needed software that will allow him to more efficiently contend in the ever competitive shipbuilding market.

The methodology behind the suite of programs referred to as "***The Connection***" will be described (Figure 1). Part of that description explains how such a program suite can provide a seamless design process resulting in lower design cost while increasing the efficiency of the design process. Additionally, the manner in which the programs are linked provides a solid base and architecture for inclusion of legacy software and hardware. One of the focal points for the selection of software was the requirement to ensure compatibility with existing programs and data.

The environments of simulation, visualization, and ergonomics are as important as the analytical design process. Without them, it would be extremely difficult to convey the intention of the design to the operators. In the case of a new and unusual design, such as the UK's trimaran, it would have been very difficult to show all the benefits this unique hull design provides. As important as the design itself is the ergonomics aspect of the hull. A hull can be designed and proven to be functional, but can be human unfriendly. Placement of equipment not only influences the design integrity of the hull, but also influences maintainability and equipment usefulness. Therefore, ergonomics affords operators and designers the benefit of visualizing equipment layout or actually simulating its operation and maintenance.

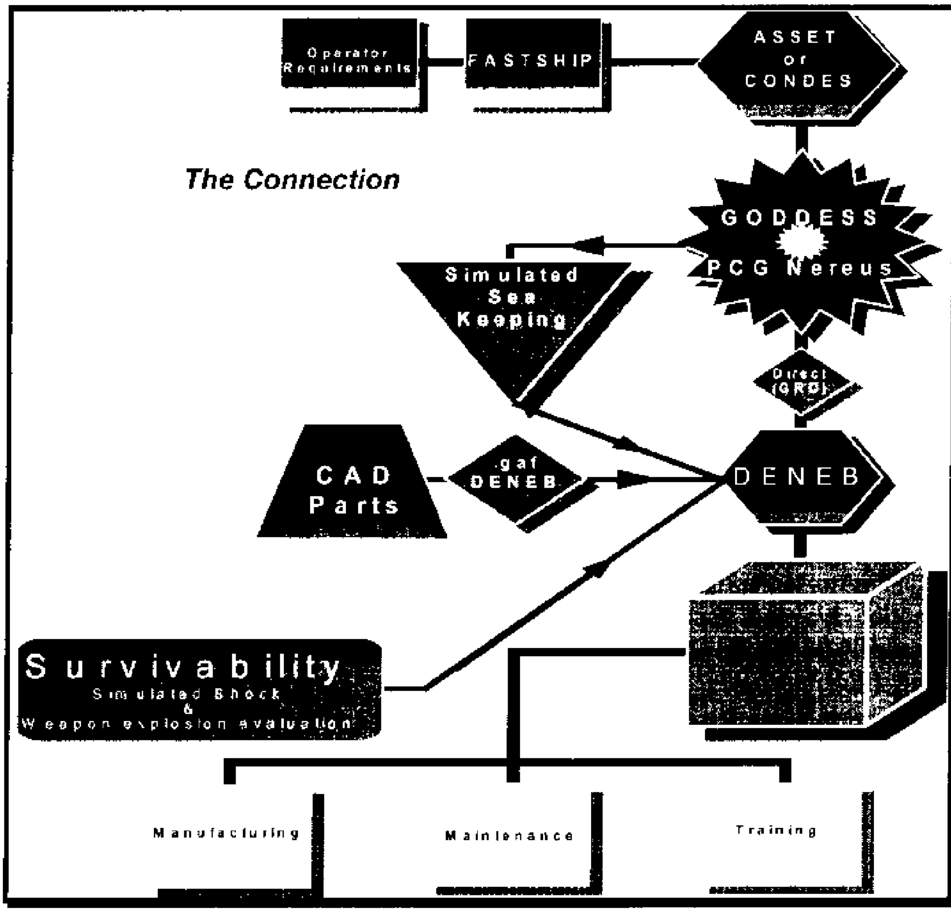
Platform survivability will additionally be discussed. Design for this feature uses data generated by either GODDESS© or PCG NEREUS as the basis for conducting survivability and weapons effect visualization and simulation. Using GODDESS© or PCG NEREUS alone, intact and damage stability can be determined for various flooding conditions.

Given this introduction, discussions will now embark on how the process works and what it can do.

Process

The process depicted in this paper relates to use of software such as that shown in Figure 1 below. This process, chosen for demonstration purposes, does not intend to convey specific endorsement of products used, rather the intent is to show potential benefit to designers, should there be a desire to seek a similar cost-saving objective.

Figure 1. "The Connection" - Modeling Design Process and End Uses



The fundamental, or initial component, in Figure 1 is the component for operator requirements. Operator requirements define items such as hull type needed to perform specific tasks. Once given operator requirements, the designer can create his initial hull form using a hull-form product such as Fastship. The hull form can then be translated into products such as ASSET or CONDES or can be directly translated into products such as GODDESS© or PCG NEREUS if desired. Regardless of the designer's product choice, the hull form becomes the basis for the preliminary hull design process.

ASSET, the U.S. Navy program, has been used for years to design warships. The suite of programs shown in Figure 1 may be used not only for warship design but also for commercial ship design.

It is at this point that the designer has enough information to begin his initial hull design. Major equipment from an existing parts catalogue can then be added to further define the hull as well as superstructure, access openings, and structural components of the ship.

Prior to discussions of the ship design suite program operation, information relative to the principle part of the design process provided by GODDESS© and/or PCG NEREUS may be helpful.

Background Data —Development of GODDESS© and PCG NEREUS

The capability for feasibility design through preliminary design to the top-level requirement stage of a ship project was the underlying requirement for the computer software which eventually became known as GODDESS©. This multi-design stage development was traditionally performed by the Ministry of Defense for all Royal Navy warships in the U.K. A major characteristic of Feasibility Design is that it requires the study of a number of options and variations as the design evolves to meet Staff Requirements.

Such work necessarily involves much routine calculation of hydrostatics, stability, weight breakdown, and layout. The principal requirement for GODDESS© was to "automate" these calculations in an organized way. There was also heavy emphasis on the use of graphics and the production of drawings so that basic general arrangement plans could be provided for more detailed layout by draftsmen.

A further point about Feasibility Design is that it was concerned with the main characteristics of the ship only - the positioning of the main bulkheads, decks, equipment, upper deck layout, resistance and propulsion, etc. This also had a significant effect on the development of GODDESS©. GODDESS© has never been intended as a detailed design tool, which could be used, for systems design and layout. Such work has traditionally been performed by the lead shipbuilder.

GODDESS© was intended to fit into this design environment as a designer's tool which could very quickly allow the assessment of the effect of changes on ship design, for example, if a main machinery bulkhead were required to be moved forward or aft. The programs and data structure were all built so that such a change could quickly be considered in a consistent manner, with the design calculations re-done, new deck plans and a new weight breakdown provided.

Similarly, when assessing damaged stability, the programs were expected to only deal with flooding between main transverse and longitudinal bulkheads. Thus the original GODDESS© suite was intended to use only a relatively simple model of the ship for analysis calculations.

During the 1980s, the use and capability of GODDESS© was expanded both as a matter of policy and as a result of demands from practicing designers. In the 1990s, the system has become a highly-developed suite of programs capable of handling ship geometries in considerable detail.

What Ship Design Processes?

A summary of ship design processes and calculations that can be accomplished using GODDESS© and PCG NEREUS programs follows:

- Hull surface design and variation
- Hull and superstructure layout
- Equipment location
- Weight and space estimation and audit
- Hydrostatic stability, intact and damaged
- Resistance, powering, and fuel consumption
- Hull bending moments on design waves
- Longitudinal hull structure and bulkhead structure
- Synthesis and analysis
- Finite Element interface
- Seakeeping analysis

- Missile arcs of fire
- Submarine weight and buoyancy
- Submarine pressure hull analysis
- Interface to specialist pressure hull analysis programs
- Production of CAD IGES output, graphs, and other printed output

Ship Description

Ship Description, such as that used in GODDESS© and PCG NEREUS, is the common database where all the information on the ship is contained. There are two major models to a full Ship Description:

- GEOMETRIC Model
- NUMERICAL Model.

The GEOMETRIC model contains the data describing the shape and layout of the ship and equipment. This model is required for work in areas such as stability analysis, structural calculations, and for producing drawings of the design.

The NUMERICAL model contains the detailed data for the weight breakdown, space breakdown, system loads, and resistance and propulsion data. It contains the majority of the information needed for the validation of a feasible design and the specification of ship systems such as electrical power, chilled water, etc.

It is a general principle of GODDESS© and PCG NEREUS that each piece of data will exist in only one place at any one time. This means it should only be necessary to create or modify a given aspect of the design once to implement that change across the entire design. The change will be recognized by other programs and will either automatically be taken into account or the designer will be prompted that a certain program or facility should be used to incorporate the change.

All files that contain ship description data are in binary format. This means that the file cannot be printed, read on the screen, or amended by a text editor, but can only be accessed by the appropriate GODDESS© and PCG NEREUS programs. This is an important safeguard to the integrity of the data, since amendments will only be properly taken into account if made by the programs.

The Hull and the Superstructure

The features of GODDESS© and PCG NEREUS ensure that the geometry is a tightly-defined and integrated set of components. There are two main "families" of compartments or modules in any ship geometry: the main hull and the superstructure. Both families are united at the top of the directory "tree."

The Hull module tree structure starts with the HULLOO compartment that initially defines the empty hull below the upper deck or main deck, that extends from bow-to-stem. This is the compartment at the "root" of the hull-module tree structure, and the empty file HULLOO.CMP is created automatically by GODDESS© and PCG NEREUS for a new design.

The tree structure for the superstructure module starts with a series of separate modules SUPER1, SUPER2, etc. These contain the geometry for each deck within the superstructure. It is not possible to divide a superstructure module by a deck. Each deck of the superstructure (i.e., 1 Deck, 01 Deck, 02 Deck etc.) must be a separate superstructure module. The various superstructure modules can be layered to represent the decks in the superstructure.

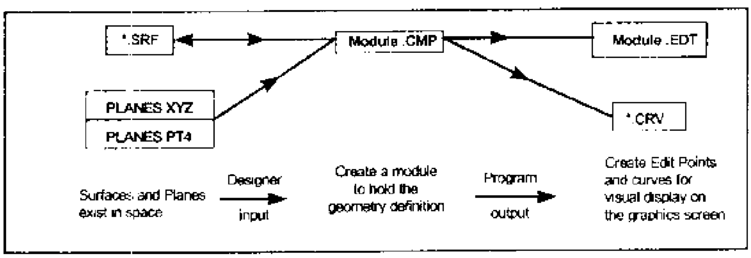
GODDESS© and PCG NEREUS use the following basic components to define the geometry of the ship:

- SURFACES - 3-dimensional arbitrary curved surfaces.
- PLANES - 2-dimensional flat planes.
- CURVES - 2-or-3-dimensional arbitrary curved lines.
- EDIT POINTS - 3-dimensional points defining the corners or vertices of modules.
- MODULES - define the topology and layout of the planes and surfaces forming a module.

The geometry of the ship is generated using surfaces and planes to create modules. The resulting intersections of planes and surfaces, or two surfaces, create edit points, lines, or curves. It is these lines and curves that are displayed on the graphics screen and give the visual impression of the layout of the modules.

Each of these components is represented by different file extensions and the basic relationships between them are illustrated in Figure 2.

Figure 2. Geometry Components



The importance of the use of surfaces and planes for the geometry lies in the fact that such entities are by definition "continuous" within their overall boundaries, which in turn allows complete flexibility over subsequent movement and where such surfaces may intersect.

Thus the GODDESS© and PCG NEREUS geometry does not require that complex shapes such as the hull-form be defined at a finite number of discrete points, such as frame stations or displacement ordinates. In contrast, a point or curve at any position on the hull can be calculated from the surface definition. These features ensure that the GODDESS© and PCG NEREUS geometry is a tightly-defined and integrated set of components.

Hull Analysis and Design Audit

Hull Analysis is comprised of the following tools. **Stability** is a comprehensive package that enables analysis of intact or damaged ship or submarine stability and plots of hydrostatic curves. The vessel condition and required analysis options are defined and the results computed and stored. These results are processed and presented in a tabular or graphical form. The characteristics of the GZ curve can be computed for calm water or when balanced on a wave and compared with criteria, while subjected to heeling moments from wind, shifted weight, or high speed turn. Other conditions include cross-flooding, fluid restrictions, critical KG, deadweight moment, margin line, and floodable length. Ship tank characteristics, including capacities, calibrations, and fluid moments, are calculated.

Ship hull resistance and propeller characteristic calculations may be carried out for single or twin screw configurations for a required ship condition (displacement, fouling, and appendages). Seakeeping analyses are evaluated using strip theory to calculate response-amplitude-operators with a choice of sea spectra. Motions are determined at a range of speeds and wave heading. Results include short or long term statistics, aircraft operability and motion sickness.

Ship strength, hull girder, grillage, panel, stiffener and plating analyses are performed. Analyses include design wave loading (to calculate shear force and bending moment) as well as in-plane and out-of-plane loading. A simplified or detailed hull section is used in analysis. Validity of design criteria is monitored. The user may investigate the interaction between weapons, sensors, and ship superstructure through the assessment of safe and blind arcs of fire. The arcs are computed from ship motion, ship and equipment geometry and weapon fire characteristics. The user can define the sea state and required probability for a particular ship and weapon combination.

Upon completion and analysis of the ship design, the design can now export information created in a program such as GODDESS© or PCG NEREUS to a visualization or simulation product. In this instance DENEB's ENVISION was employed. By using ENVISION another step was eliminated in the overall prototyping process.

An understanding of DENEB's ENVISION software may be helpful to the understanding of the overall process:

Designers use **ENVISION VE's** interactive physics-based, 3-D graphic models to accurately visualize and evaluate concept designs for complex systems and subsystems. The CAD-based models precisely represent the actual geometry and motion characteristics associated with the real-world system.

ENVISION VE, VP, and VR feature advanced graphics including:

- Camera model for visualization
- Multiple light sources
- Texture maps
- High speed rendering
- "Level of Detail" management.

ENVISION VP enhances the VE system by incorporating dynamics into the physics-based models to create a virtual environment that supports simulation based design. In this environment, users are able to design, build, test, operate, and support multiple product and system scenarios in a fast, efficient, and cost-effective manner.

- Complex mechanical designs
- Rigid body dynamic analysis
- Mobile systems/vehicles
- Satellite design and deployment
- Design verification
- Concurrent engineering
- Human factors engineering (optional)
- Mission planning
- Space task engineering

ENVISION VR Virtual Reality

ENVISION VR for Virtual Reality (VR) provides a powerful environment for designing and programming complex design, engineering, and training operations by allowing the user to interact more directly with the simulation environment. Users can fly and walk-through the simulated environment using virtual reality and telepresence techniques to operate devices, alter the environment by relocating components, or otherwise interact with the virtual world. Options are available to support multiple person simulation and Virtual Collaborative Engineering. ENVISION VR was specifically designed to provide high fidelity and high-speed system interaction. Selected features include:

- Alternative display technology
- Geometric representation of immersed objects
- Interaction between immersed objects and simulated world
- Position tracking
- Event handling
- spatial sound (optional)

In addition, a wide array of visual display systems, position and object tracking systems, and event feedback devices are supported.

Simulation Based Design

ENVISION VE and VP support form, fit, and function evaluations. Designers can analyze component placement and system configuration to optimize operations. DENEB's virtual environment automatically detects component collisions.

Multiple what-if scenarios can be rapidly explored during initial design and trade studies to determine the best concept before design closure.

Concurrent Engineering

ENVISION VE, VP, and VR enable engineers to efficiently interact with proposed designs early in the development cycle. The benefits include significant cost savings resulting from thoroughly assessing the ability to produce and maintain designs and minimizing or eliminating expensive tooling changes during the development cycle, dramatically faster response to changes in the market, and greatly reduced product launch cycles.

Simulation Based Training

The ENVISION VE, VP, or VR model makes for an ideal training environment. Simulation based training can begin before fabrication or installation. End-users can use the model to achieve proficiency in operating and maintaining systems and subsystems without risk to operators or equipment.

Human Factors Engineering

DENEB provides the industry's first commercially available human model fully integrated into a design environment. With the DENEB/ERGO option, human factors can be evaluated and ergonomic issues like Design For Assembly (DFA) can be resolved by both the designer and the end-user early in the design process. Users can rapidly prototype and analyze human motion, including:

- Reachability
- Field of view
- RULA posture analysis
- NIOSH lifting guidelines
- Garg's energy expenditure (k-cal/hr. prediction model)
- MTM-UAS analysis for accurate activity timing

After completing the translation of the ship design data from products such as GODDESS© or PCG NEREUS into the DENEB ENVISION software, the 3-D CAD part created on CAD systems can be translated into the model. This allows the designer to use existing 3-D CAD part from other ship design programs, from equipment vendors, or from a library created by other government agencies (e.g., Air Force, Army, etc.). One method developed used a translator called a .gaf translator. This translator was developed by DENEB to accommodate existing AEC Dimension III and Cadds 4 library parts and models. This translator has been proven very efficient and reliable with its use at the DDG 51 Flt IIA SET. Other existing translators can also be used to facilitate the inclusion of existing library parts. This is a very important part of the overall process since the need to remodel these parts is eliminated. This is not to say that library parts will not have to be modeled; rather, the use of existing library parts should be fully exploited. As new equipment is developed, 3-D, CAD library parts will need to be created. Accordingly, designers should check with the vendor creating the equipment to see if 3-D CAD models are available.

As mentioned before, the GODDESS© and PCG NEREUS have the ability to generate simulated Seakeeping data. This data has been compared to actual in-service ship Seakeeping recorded data over a 1-year period aboard a UK Frigate. The compression revealed the reliability of the simulated Seakeeping data and has been accepted as valid by the UK Ministry of Defense (Mod). The advantage of using simulated Seakeeping data allows customization to the exact condition under study. Using this data in the DENEB ENVISION environment allows the design to evaluate equipment in varying sea conditions. This value-added feature affords the designer confidence in joint evaluation results without the effort of additional programming.

All the aforementioned elements of this suite of programs go together for ***"The Connection"*** (Figure 1) which produces a 3-D Virtual Prototype model suitable for use in manufacturing, training, and maintenance. The final feature added is Survivability. This feature includes weapons effects and simulated shock. It is anticipated that this feature will be available in the latter part of 1999.

Case Studies

As a prelude to this paper, George G. Sharp, Inc. (SHARP) conducted two Internal Research and Development studies. Study one was based on the need to develop a physics-based model of an existing Hull that had no 3-D CAD models. Study two was based on the need to modify an existing DDG 51 compartment. Internal Research and Development objectives were:

- Translate design **quickly** into prototype for evaluation against requirements
  - — Common interface of "tools" for trade-off studies and modifications ... easy to use and inexpensive
- Validate the ability to determine and correct interference and producibility problems
  - — 3-D Virtual Prototype model that is physics-based
  - — Provide a visual and physics-based environment for equipment routing and maintainability
- Establish a baseline for hull creation in GODDESS©
- Establish a baseline for translation of GODDESS© model and existing library parts into a Virtual Environment
- Verify ergonomics.

Study 1

This study was conducted in order to establish a baseline for future existing hull modification. An existing FFG 7 hull was selected which had no previous 3-D CAD models. Copies of 2-D drawings were retrieved using the Advanced Technical Information Support System (ATIS). The line drawings were then digitized into GODDESS© and a 3-D physics-based model was created. Since this was an existing hull and only selected compartments were to be addressed, the VCG and weight were input into GODDESS© to establish the baseline (it is anticipated that this will become the standard procedure for existing hulls). All ship analysis functions were then tested on this hull form. This task took 120 Man-hours (see Figure 3).

It is at this point that Seakeeping data could be extracted from the GODDESS© model and be readied for the simulation. Additionally, any ship alteration could be evaluated in this model to determine its effect on the integrity on the hull. Next the polygonal surfaces were extracted from the GODDESS© models and imported into DENEB ENVISION software via .stl format.

This study was designed only to establish a baseline so rather than models all compartments in the ship, Auxiliary Machinery Room (AMR) 2 was selected for part propagation. Since no 3-D models or parts existed for this class of ship, it was necessary to create the library parts for AMR2. Due to the uniqueness of the wireways and HVAC, it was decided not to model these components. In keeping with the overall concept of this procedure it was decided to use existing DDG 51 class 3-D parts wherever possible. Therefore parts such as lights, ladders, and standard equipment cabinets were translated using a .gaf and inserted into the AMR2 model. This task took 475 Man-hours (see Figure 3). The remaining library parts were then assembled in the ENVISION software, ergonomics added, and equipment and visualization paths established. This task took 90 Man-hours (see Figure 3). At this point the model was ready to be used for simulation purposes. Kinematics and Dynamics can be assigned to part or joints, simulation data (such as Seakeeping) can be applied, and simulation/studies executed. This effort produced a 3-D physics-based CAD model capable of supporting a variety of studies and simulations.

The final phase of this study involved adding the correct lighting for AMR2 as well as representing the surface textures of the components in the space. This effort involved adding 68 light sources and producing a rendered video fly-through of both levels of AMR2. It should be noted that each represented light source carried the correct lumen value for that light fixture type. This task took 712 Man-hours of which 672 were computer hours used to render the 7200 frames (see Figure 3).

Figure 3. AMR2 Man-Hour Modeling Requirement

AMR2 Actual Man-hours	
GODDESS©	120 Man-hours
3D Equipment Modeling	475 Man-hours
3D Prototype	90 Man-hours
TOTAL	**685 Man-hours**
Addition of Lighting	40 Man-hours
Rendering Time	672 Computer-hours

Study 2

This study was developed for the DDG 51 Program and involved the translation of existing 3-D CAD parts and models into a virtual environment for the purpose of evaluating the feasibility of placing a large pulper unit in an existing space. Not only was this model used for space and maintenance evaluation, it was also used to evaluate ergonomics. As shown in Figure 4, the translation of the CAD models and parts took only 10 man-hours. This in itself substantiated the theory of *model once, use many times*.

In this study a 95th percentile male android was inserted into the model and made to perform a minor maintenance task, i.e., removal of one of the access panels behind the pulper. Although the space was limited, he could perform the task, thus validating the arrangement. However, when the 50th percentile male android was inserted to perform the same task, he was unable to reach the same equipment as did the 95th percentile android. This simulation provided the designers with the necessary information to allow him to make minor modifications to the arrangement and to re-conduct the simulation. With the modifications in place, the simulation was rerun with the desired effects.

It is important to note that the design review of this space was conducted via a VTC with approximately 15 people in attendance. This entire effort, including the VTC, took 110 Man-hours as shown in Figure 4. As an afterthought, it was decided to evaluate the lighting conditions in this space. The space is an existing reefer space with stainless steel bulkheads and 8 light sources. Upon completion of the rendered video, it was determined that the light intensity was sufficient for the space involved. The addition of the light sources and the computer rendering time was 48 Man-hours as depicted in Figure 4.

Figure 4. Trash Room Man-Hour Modeling Requirement

Trash Room Actual Man-hours	
3D Equipment Modeling	10 Man-hours
3D Enhancement & Simulation	100 Man-hours
TOTAL	**110 Man-hours**
Addition of Actual Lighting	8 Man-hours
Rendering Time	40 Computer-hours

Key Benefits of Integrated Design and 3-D Prototype Systems Using Described Process:

- Reduces simulation/evaluation time resulting in the reduction of overall ship design cost and delivery schedule.
- Eliminates need to remodel for simulation purposes.
- Provides ability to use already developed design data.
- Provides opportunity to use existing 3-D parts created for other programs.
- Provides a "Physics-based" 3-D Virtual Prototype model.
- Uses "***off-the-shelf***" hardware and software.
- Compatible with both UNIX and NT workstations.
- Provides "Start to finish" integrated system.
- Provides simultaneous evaluation, reconciliation, and prototyping.
- Provides opportunity to use Conceptual Design Model to create "Product Model".

As shown in Figure 5, the Unforeseen Potential Savings far outweighs the acquisition cost of the hardware and software.

Figure 5. Unforeseen Potential Cost Savings

LHD

Ship	Acquisition Cost	Change Order Costs	Unforeseen Potential Savings
LHD1	$996M	$80M	$16M
LHD2	$403M	$42M	$8.4M

$ 24.4M

DDG-51

FY	Ships to be Built	Acquisition Cost	Change Order Costs*	Unforeseen Potential Savings
95	3	$2,642M	$79M	$15.8M
96	2	$2,194.2M	$66M	$13.2M
97	4	$3,384.1M	$102M	$20.4M

* - Based on 3% of the Acquisition

$ 49.4M

Open Systems

Portability is one of the most important issues facing developers and users today. Ship and submarine projects demand similar functionality and look and feel over the whole spectrum of systems available to them. Portable software intended for several platforms from inception, providing interface, services, and supporting formats enable GODDESS© and PCG NEREUS to:

- be ported across a range of systems with minimum change
- work with other applications on local or remote systems
- interact with its users with a look and feel which facilitates user portability.

A Top Level Program

A top level supervisor program aids system navigation. This manages the users' data, provides work logging and context sensitive help facilities and a tutorial service. The result is that new users are able to quickly use the system in an effective and efficient manner.

Software Profile- ***O.S. Standards***

Operating System— Posix (ISO 9945)
Languages — FORTRAN 77, (ISO 1539), C (ISO 9899)
Graphics — PHIGS (plus) (ISO 9592, 9593)
User Interface — X Windows MOTIF
Networking — TCP/IP NFS NIS
Data — POSTSCRIPT CGM IGES HPGL
Documentation — SGML

Hardware Profile (Optional Capacities)

PCG NEREUS:
NT Operating System 32 Mb Memory

GODDESS©:

UNIX Operating System
FORTRAN 77 and C Compiler
Color Monitor 19" screen 1280 x 1024 Non Interlaced
Hard Discs: 1 x 1 Gb, 1 x 400 Mb
Floppy Drive DAT Tape CD ROM
ASCII Keyboard
Mouse
A3 Color Plotter

Conclusion

Although cost savings are not quantifiable at this time, they are inherent in this one-model approach. The approach itself is pointed at cost avoidance through reduction of engineering changes. Currently 10% of Naval acquisition costs for a lead ship and 5% for follow ships are earmarked for changes. A reduction of 20% of funds earmarked for changes represents a significant savings to programs. These savings can be achieved.

Acknowledgements

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Ronald P. Saber is the Modeling, Simulation and Virtual Prototyping Manager at George G. Sharp, Inc., Alexandria, Virginia. His 28 years of design experience, including 10 years devoted to CAD Visualization and Simulation, are primary to his current position. A proficient and knowledgeable database professional, Mr. Saber's expertise in Naval engineering, shipyard operations, and general structural/mechanical engineering paves the way for his innovative applications of current technology in marine 3-D modeling and simulation.

DIVA3D, A 3D LIQUID MOTION NEW GENERATION SOFTWARE

Mr. Laurent Brosset, Mr. Tung Thien Chau, IRCN, Nantes, France
Mr. Michel Huther, BUREAU VERITAS, Paris, France

Introduction

Industry discovered sloshing phenomenon in the 70's when large size tankers and LNG carriers were first built in Europe and Japan. The problem at that time was solved through small size model tests as the numerical tentatives failed due to the computing capacity limitations [Ref 1-2-3]. From the model test results and theoretical development, Bureau Veritas published a guidance note in 1984 [Ref 4]. No more development occurred in 3D numerical approaches form this period until the computing means allowed to consider possible to solve the liquid motion equations.

So IRCN, the French Research Shipbuilding Institute, jointly with CISI, a French Software Company, has developed a new software for 3D simulation of the highly non linear liquid behaviour in moving tanks, with a view to addressing especially the liquid motion problem in partially filled tanks of different kinds of ships such as LNG carriers, crude oil carriers, FPSO.

This software, named DIVA3D, is based on the discretization of the Navier-Stokes equations for both phases (liquid & gas) thanks to a finite volume scheme. The tank may be imposed any motion. An improvement of traditional techniques, tracking the « volume of fluid » [Ref 5] in each cell, has been brought in order to handle the free surface avoiding the numerical diffusion which generally accompanies the treatment of sharp discontinuities. In this way, DIVA3D allows to simulate complex three dimensional flows including breaking waves or liquid splashes.

After having presented the theoretical basis, which DIVA3D rests on, the paper deals with the validation aspects : specific LNG tanks model tests have been carried out focusing on free surface video recordings. Significant examples are presented showing a good agreement between DIVA3D calculations and measurements.

Different applications in shipbuilding are proposed in the following section of the paper, concerning the determination of resonant cases by means of kinetic energy comparisons, tank shape influence on liquid motions, or load calculations on internal elements.

The last section of the paper deals with the present development activities which focus on the implementation of an interface between DIVA3D and the finite element explicit LS-DYNA software [Ref 7] in order to simulate the fast dynamic response of tank walls under sloshing impacts.

Theoretical basis

Mathematical formulation

There are two phases within the tank (liquid and gaseous phases). It is assumed that there is no thermal phenomenon. Consequently, the physical problem is described by two of the Navier-Stokes equations (mass and momentum conservation). No thermal phenomenon implies that there is no exchange of mass between the two phases: one liquid particle remains one liquid particle, one gaseous particle remains one gaseous particle. Thus, a scalar α field defined as $\alpha = 1$ for any liquid particle, $\alpha = 0$ for any gaseous particle is conservative. The discontinuity surface of α field is of course the free surface and the α field conservation equation looks like a free surface equation. Furthermore, α field allows to adopt the rule of mixture. The mixture density is $\rho = \alpha\rho_l + (1-\alpha)\rho_g$ where ρ_l and ρ_g are respectively the liquid density and the gas density.

DIVA3D solves the Navier-Stokes equations written in a reference system attached to the tank [Ref 5].

Both phases are viscous. The liquid phase is incompressible while the gaseous phase is slightly compressible and follows the equation of state $p = \rho_g c^2$ where p is the pressure and c the speed of sound in the gas.

Different friction laws are available as boundary conditions. But in any case, the tank walls are considered as rigid.

Tank kinematics

The tank may be imposed any motions which are described as follows:

- one translation defined by the three coordinates, in the fixed reference system, of the origin of the moving reference system attached to the tank;
- one rotation defined either by the Euler angles or by the coordinates in the fixed reference system of the instantaneous rotation vector.

The evolutions in time of these six parameters are given either as a sum of harmonic functions or in tabular form. In the second case, the software interpolates the punctual data by cubic splines. At each calculation time step, DIVA3D is thus able to determine the gravity and the inertial accelerations and to take them into account in the momentum conservation equation written in the moving reference system attached to the tank.

Discretization of equations

The discretization is performed on a one-block parallelepipedic meshing (Fig.2-1) by the finite volume method. The size of the cells may vary in each axis direction. At each calculation time step, the unknowns of the problem are the mean values of the pressure and of the α field in each cell side (Fig.2-2).

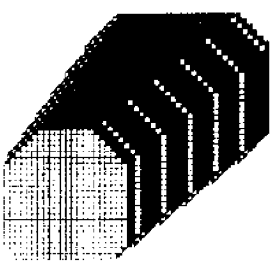


Fig.2-1 : DIVA3D Parallelepipedic meshing of the fore tank of a membrane LNG carrier

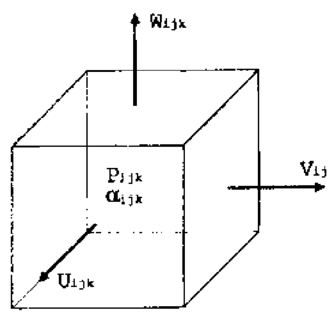


Fig.2-2 : DIVA3D unknowns defined on one elementary cell (i, j, k)

In fact, each projection of the vectorial momentum equation on one of the moving reference system axes, is discretized on a meshing staggered by half a cell from the original mesh (Fig.2-3) in the considered direction.

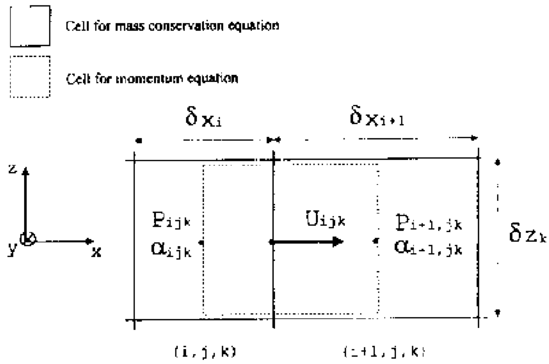


Fig.2-3 : Staggered mesh for the momentum equation discretization

Such parallelepipedic meshing does not fit inclined walls. So corrective parameters are introduced into the discretized equations in order to take into account the actual fluid volume (liquid + gas) within each cell cut by one boundary plane, or the actual fluid surface within each cell side cut by one boundary plane.

The α field appears after discretization as the filling rate of the cells by the liquid phase. It may therefore have numerically any value between 0 and 1. In order to avoid or limit the effect of liquid spreading (numerical diffusion) related to methods derived from Volume of Fluid Method (V.O.F.) [Ref 5], the free surface is materialized in each concerned cell by a plane the normal direction $\vec{n}$ of which is given by the gradient of α . The knowledge of α and $\vec{n} = \overrightarrow{grad}\ \alpha$ allows to determine the exact location of the plane. The liquid flow is then allowed only through the wet parts of the cell sides. Their formulation does not lead to limitations existing in most of the 3D sloshing programs such as non contiguous free surface. It allows to simulate impulsive loads on tank walls, wave overturning and breaking.

At each time step, the implicit pressures are substituted to the velocities projections, thanks to the vectorial momentum equation, into the mass conservation equation. This leads directly to a linear system in pressure solved by a conjugated gradient method preconditionned by an incomplete Cholesky algorithm.

Validation

Introduction

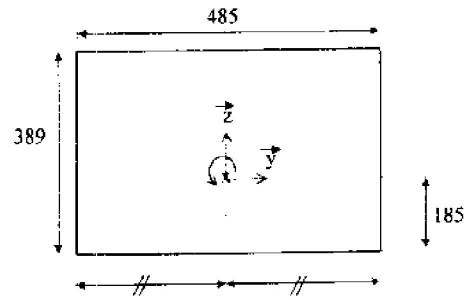
During the development of the code, the first step of the validation was carried out with academic cases in order to check the influence of the different terms of the inertial accelerations in the momentum conservation equation. For instance, the shape of the free surface at equilibrium state was checked for excitations such as uniform rotations around different axes or uniformly accelerated translations.

In a second step the DIVA3D results were compared with published results coming from either other calculations or measurements. Finally, in order to be able to validate DIVA3D in sufficiently varied situations, it was decided to perform tank model tests. These tests aimed to videotape the free surface motions with a CCD camera (25 images/s) fixed to the tank. The tank motions were forced by a servo-control system.

About one hundred cases were studied resulting from the following parameters combination:

- 2 tank models (1/ parallelepiped 485 x 487 x 389 mm ; 2/ same with longitudinal chamfers);
- 2 types of harmonic motions (pitch and roll);
- 3 filling ratios (15 %, 50 %, 90 %);
- 2 amplitudes (1°, 3°);
- frequency scanning to seek possible resonant cases.

Two significant cases are presented below. They are related to the parallelepipedic tank model subjected in both cases to harmonic roll motions of maximum amplitude 3°.



$\theta = \theta_0 \sin 2\pi f t$

$\theta_0 = 3°$

f : *frequency*

t : *time*

Fig. 3-4: Tank features and roll motion axis location

These two cases respectively correspond to filling ratios with typical different liquid motions, R = 15% and R = 50%. All the DIVA3D calculations, the results of which are presented hereafter, were performed with the same regular 50 x 40 x 1 meshing. The comparisons focus on the free surface shapes at different times.

The DIVA3D results have the following forms:

- grey graduation related to filling ratios of the cells.
- fluid velocity vector in each cell. In this representation an added line gives the free surface location.

It is important to note that the DIVA3D calculations were performed with the actual model tank motions as it was precisely sampled (every 5 ms) during the experiments. Due to the experiment test rig, the actual signal is far from the pure sinus curve so the DIVA3D results were obtained with the real excitation signal modelization.

Low filling ratio: 15%

The actual excitation which was reused for DIVA3D calculation is shown on Fig.3-5 and Fig.3-6 (frequency: 0.7 Hz ; Amplitude : 3°)

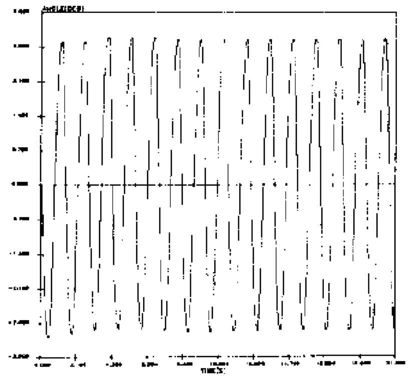


Fig.3-5 : Actual roll motion subjected by the tank during the experiment and reused for DIVA3D calculation

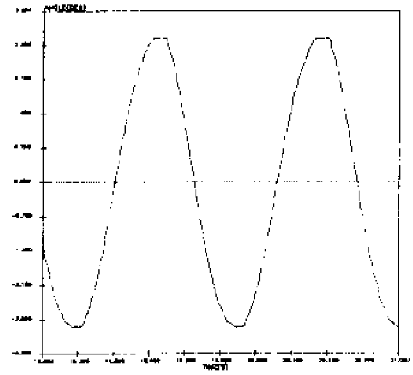


Fig.3-6 : Detail of the curve on fig.3-5

R = 15% - f = 0.7 Hz – A = 3°

The results at time t = 17.92 s are presented on Fig.3-7 to Fig.3-9;
The results at time t = 20.12 s are presented on Fig.3-10 to Fig.3-12.

Fig.3-7 : t = 17.92 s Video record

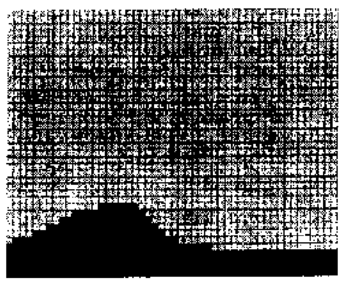


Fig.3-8 :t = 17.92 s Grey graduation related to filling ratios

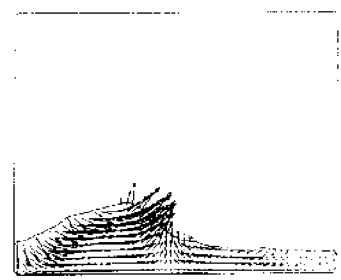


Fig.3-9 : t = 17.92 s Fluid velocity vectors

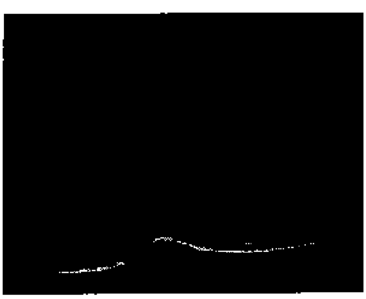


Fig.3-10 : t = 20.12 s Video record

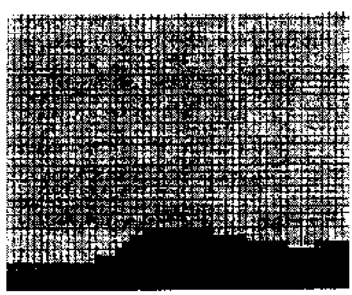


Fig.3-11 : t = 20.12 s Grey graduation related to filling ratios

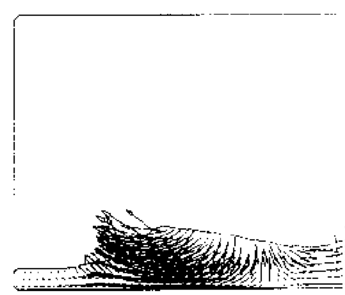


Fig.3-12 : t = 20.12 s Fluid velocity vectors

Rectangular tank – Harmonic roll motion
R = 15% - f = 0.7 Hz – A = 3°

The progressive wave which runs through the tank is simulated with a pretty good precision by DIVA3D along the whole duration of the excitation motion.

High Filling ratio: 50%

During the experiments, the resonant case with amplitude 3° had been detected by scanning the excitation frequency by steps of 0.01 Hz and comparing the corresponding maximum free surface elevation on video records. Thus, the resonance frequency value had been assessed at f = 1.15 Hz. A similar process was followed with DIVA3D simulations for harmonic excitations. For each excitation frequency addressed, the relative kinetic energy in the tank was calculated as a function of time. The curve giving the maximum value of kinetic energy versus excitation frequency is presented on Fig.3-13. It presents a clear resonance peak centered on the frequency value f = 1.149 Hz.

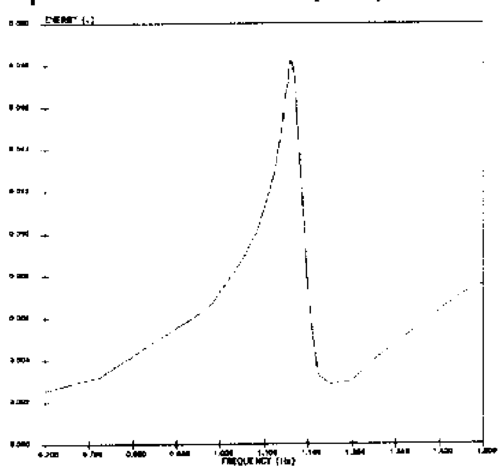


Fig.3-13 : Maximum relative kinetic energy in tank versus roll frequency
Rectangular tank - Harmonic roll motion
R = 50% - f = 1.15 Hz – A = 3°

Thus, this method based on kinetic energy calculations from DIVA3D flow simulations proved to be very accurate.

This can be a major point for non conventional tank shapes or for tanks with stiffeners inside or for large motion amplitudes because for all these cases the usual analytical formula coming from linear potential theory becomes unreliable.

In the following, the flow as recorded during the experiment at resonance frequency (f = 1.15 Hz) is compared with the virtual one simulated by DIVA3D in the same conditions (i.e. with the actual excitation signal).

The results at time t = 30.50 s are presented on Fig.3-14 to Fig.3-16;

The results at time t = 30.94 s are presented on Fig.3-17 to Fig.3-19.

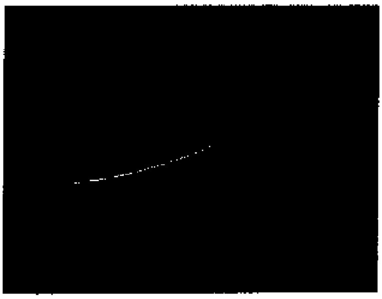


Fig.3-14 : t = 30.50 s Video record

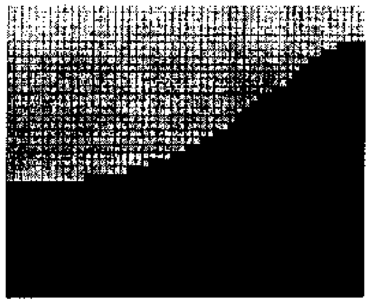


Fig.3-15 : t = 30.50 s Grey graduation related to filling ratios

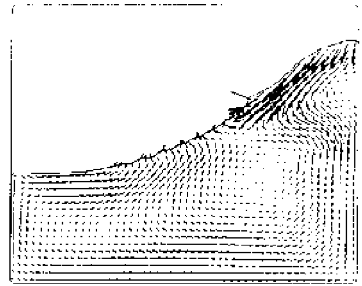


Fig.3-16 : t = 30.50 s Fluid velocity vectors

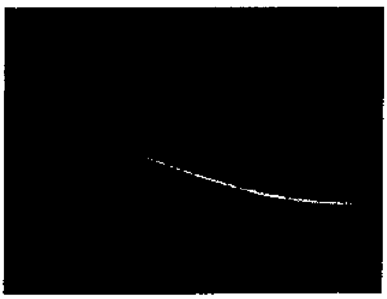


Fig.3-17 : t = 30.94 s Video record

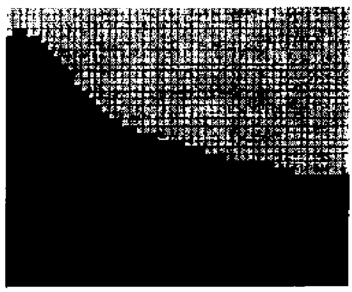


Fig.3-18 : t = 30.94 s Grey graduation relation related to filling ratios

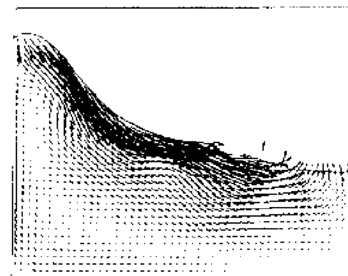


Fig.3-19 : t = 30.94 s Fluid velocity vectors

Rectangular tank – Harmonic roll motion
R = 50% - f = 1.15 Hz – A = 3°

Here again, we can observe that the DIVA3D simulation of the flow gives a fairly good representation of the reality all along the whole test duration (≈ 35 s).

Applications in shipbuilding

The validation on academic cases being positive, it has been performed applications on ship tanks with partial filling.

The selected cases correspond to model test studies performed in the past, but also to real ship tanks for which sloshing observations in service were available at Bureau Veritas.

Some flow examples in tanks of membrane LNG carriers

Each case presented below is related to the fore tank of one LNG carrier with membrane prismatic tanks. An average size of these kinds of tank is 35 000 m^3.

The examples have been selected for their capacity to show the possibilities of DIVA3D for simulating complex three dimensional flows. They correspond to model test cases but not to navigating conditions.

Fig. 4-1 Filling ratio 13% - Pitching motion
Resonance frequency - Amplitude 7°

Fig. 4-2 Filling ratio 40 % - Roll motion
Resonance frequency - Amplitude 20°

Fig. 4-3 Filling ratio 70% - Pitching motion
Resonance frequency - Amplitude 7°

Fig. 4-4 Filling ratio 90% - Pitch and Roll motion combined
Pitch amplitude 4° – Roll amplitude 6°

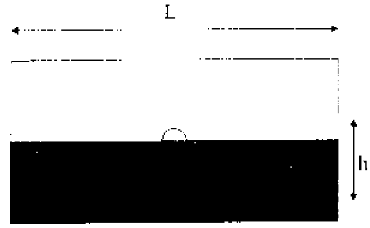
Such calculations require quite refined meshings of the tanks (commonly more than 25 000 cells) which demand important computing resources: the software is set up in IRCN on a Silicon Graphics Power Challenge R10000. A typical simulation of one minute corresponding flow in an LNG tank requires between one and two CPU hours on this server but using a not optimized version.

Search of resonance periods

One basic rule a Naval Architect must keep in mind when designing a liquid cargo ship is to avoid that the liquid natural periods in the tanks are in the vicinity of the ship motions periods. For getting an approximation of the natural liquid periods, one very simple and often efficient tool is available, the well-known formula, derived from of the linear potential theory for parallelepipedic tanks:

$$T_0 = 2\pi \Big/ \sqrt{\frac{\pi g}{L}\, th\left(\frac{\pi h}{L}\right)}$$

where T_0 is the first natural period



The accuracy of the result depends mainly on the respect of the hypotheses assumed for obtaining the formula: the closest the tank shape is to a parallelepiped and the smallest are the non linear effects, the more accurate is the formula. It means in particular that in the following cases the formula is not relevant or at least imprecise:

- complex tank shapes, in particular with internal stiffeners;
- small filling ratios for which progressive waves can develop;
- high filling ratios for which the ceiling interacts strongly with the free surface;
- large amplitude excitation motion.

For all these cases, the already mentioned method, based on kinetic energy criterion applied on a set of DIVA3D simulated flows, is efficient. One DIVA3D calculation is performed for each excitation period scanning the potential period range of the ship for the selected elementary motion. For each period, the relative kinetic energy in tank is calculated as a function of time, which allows to build the curve of maximum kinetic energy versus excitation period. At one resonance condition corresponds one peak on the curve.

The following example corresponds to the study of one tank of a VLCC subjected to harmonic pitching motions. The tank is parallelepipedic but is provided in the middle by a swash bulkhead (Fig.4-5). The filling rate of the tank is 60% of tank height. The pitching amplitude is 3 degrees.

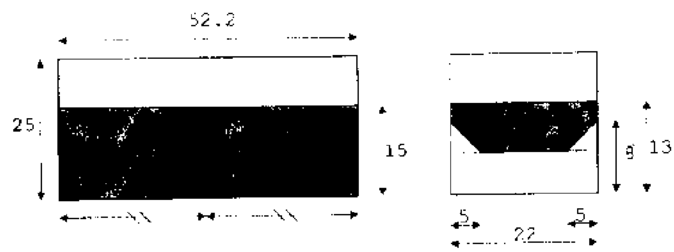


Fig. 4-5 Main features of the studied tank

After performing about twenty 3D calculations with DIVA3D, the application of the above described kinetic energy criterion based method provides a curve which shows a peak centered on the period $T_0 = 10.9$ s. The analytical formula would have given $T_0' = 12.57\ s$ without the swash bulkhead.

The method proves to be quite sensitive as attested by the following example based on the parallelepipedic tank model which was used during the validation model tests mentioned in the previous section (Fig.3-4).

The tank is now subjected to a pitching rotation the axis of which is moved back (1.21 m) as it would be the case if the tank were at the fore part of a ship. The filling rate is 70%.

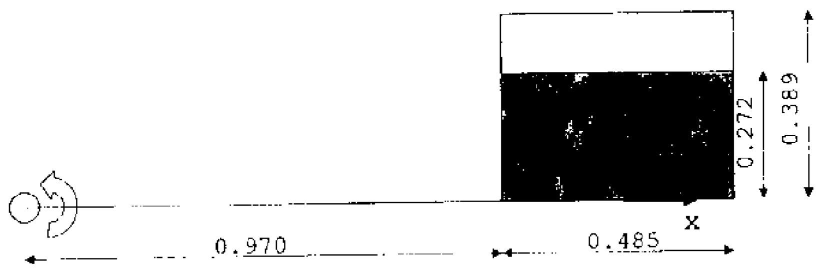


Fig.4-6 : Tank features and pitch motion axis location

The search of resonant period was driven as previously for a moderate pitch motion (1 degree). It led to the following kinetic energy versus period curves on Fig.4-7.

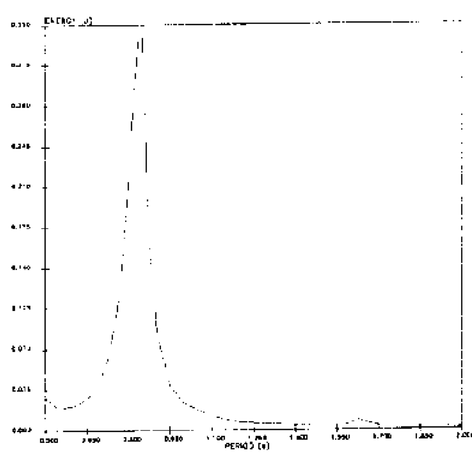


Fig.4-7 : Maximum kinetic energy versus pitching period for a rectangular tank model R = 70 % - A = 1°

The curve shows a very marked peak centered on the period T_0 = 0.84 s, which is related to the first liquid mode. The use of the analytical formula would have given $T_0^* = 0.81\,s$. (All conditions are gathered for an accurate use of the formula) but a second small peak can be observed on the curve centered on the period T_1= 1.63 s.

Let us compare the flows obtained at respectively T = T_0 et T = T_1 through their relative kinetic energy time histories (Fig. 4-8 and Fig. 4-9).

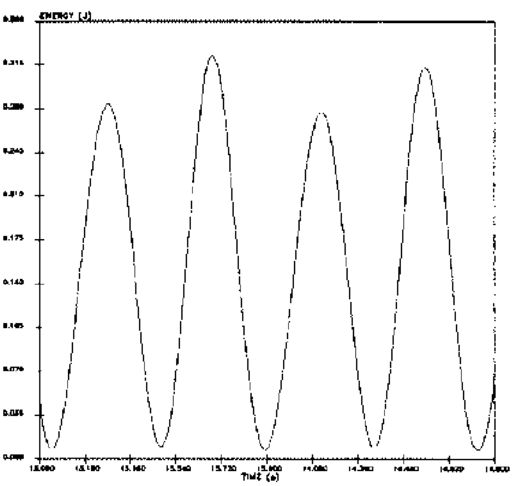


Fig. 4-8 kinetic energy time history for $T = T_0$

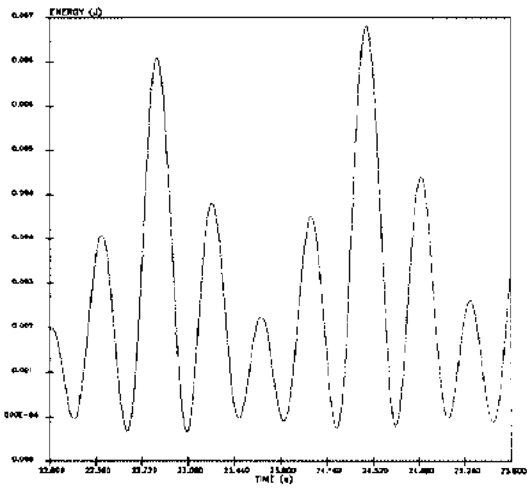
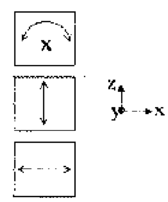


Fig. 4-9 kinetic energy time history for $T = T_1$

In both cases, after a moving off stage, the liquid oscillations become regular. In the first case ($T = T_0$) there are two energy peaks during one period. These peaks correspond to flow through and back respectively. In the second case ($T = T_1$) there are four energy peaks, which means two through and back liquid motions during one pitching period. It looks like a liquid motion forced twice quicker than the pitching motion.

It can be easily proved that the tank motion resulting from ship pitch motion is, up to the second order, dynamically equivalent to the superposition of three elementary tank motions:

- One pitching motion around the tank center (around y direction)
- One heaving motion (in z direction)
- One surge motion (in x direction)



The last one pulsates twice quicker than the ship pitch motion. It means that its period is T/2. Therefore, when $T/2 = T_0^{'}$, the resonant liquid motion in surge is excitated: $T_0^{'} = T/2 = 0.815$ s. Nevertheless, some convergent experimental and computing results make us think that the gap is due to the influence of the motion amplitude on the natural period. The natural period increases with the motion amplitude.

Thus the amplitude of pitch motion being larger than the amplitude of induced surge motion, we found effectively $T_0 > T_0^{'}$.

Also, it can be noted that $T_0^{*} = 0.81\,s$, the theoretical first natural period for either pitch or surge motions, is closer to $T_0^{'}$ (small motions with less non linear effects) than to T_0 (large motions).

Tank shape influence

The following results illustrate the ability with such a numerical tool as DIVA3D to check quite easily the influence of shape tank modifications on the inner liquid motions.

Two DIVA3D calculations have been performed for the second tank (Fig. 4-10) of a 135 000 m^3 membrane LNG carrier, filled at 90% of its height and submitted to resonant roll motion T = 7.0 s of magnitude 7°.

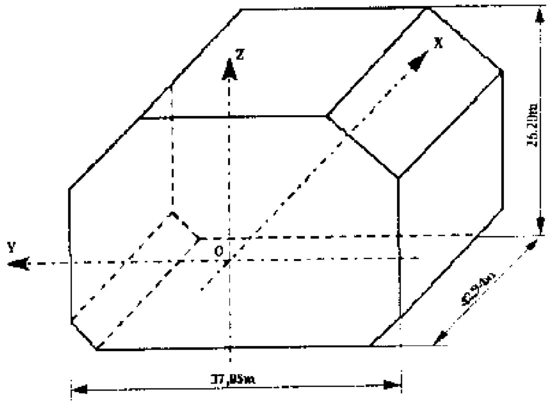


Fig. 4-10 Tank n°2 of a membrane LNG carrier – Roll motions

The first calculation concerns one tank shape version with small upper chamfers (14% of tank height). The second one concerns one other tank shape version with large upper chamfers (30 % of tank height). The results are given in the form of velocity vectors in the liquid phase at the same four different instants in the two tanks. The four instants are regularly spaced in one roll period.

The left column below is related to the small upper chamfers tank

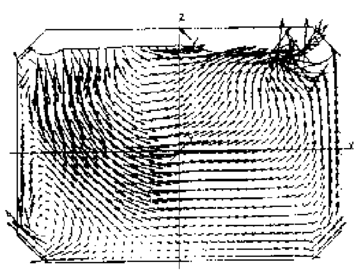


Fig. 4-11 t = 127.75 s

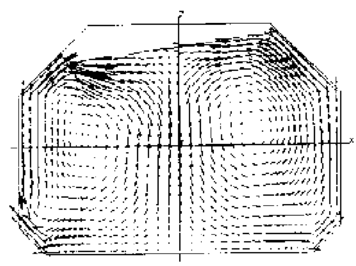


Fig. 4-13 t = 127.75 s

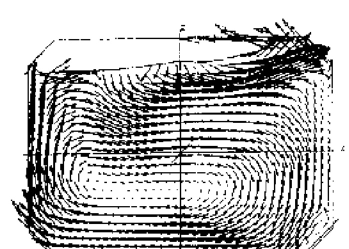


Fig. 4-12 t = 129.5 s

Small upper chamfers

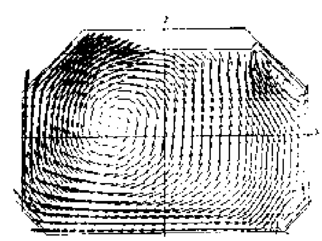


Fig. 4-14 t = 129.5 s

Large upper chamfers

Velocity vectors as simulated by DIVA3D at four different instants – Roll motion T = 7.0 s ; A = 7°

The benefit of using large upper chamfers is clear when watching the previous figures. With the small upper chamfers, the highest part of the liquid shows strong impacts in the upper corners. With the large upper chamfers the free surface motions seems to be mitigated by the effect of two vertical vortex. No impact appears.

Numerical simulation of sloshing impacts

Introduction

One of the most important issues resulting from liquid motions in partially filled tanks is the structural response to sloshing impacts.

This problem was usually dealt with, by measuring impact pressures on model test tank bulkheads by means of pressure gauges with very high natural frequencies (> 100 000 Hz). These pressures were often extrapolated to the full tank scale thanks to means of similarity laws and then compared to a maximum admissible pressure.

This process presents several shortcomings :

- several physical phenomena occur simultaneously in fluid/structure impacts while the similarity law takes only one into account;
- not only the maximum pressure to be applied is important to know the structural response but also obviously the time duration because of dynamic behaviour;
- fluid and structure problems should not be separated in such a way. Impact pressure is not a shock wave pressure but is an internal parameter of a coupled problem. For instance, the maximum pressure depends on the local rigidity of the structure part on which it is applied.

For all these reasons, IRCN decided to address the sloshing impact problem by interfacing its DIVA3D software with a finite element code using an explicit time integration method for simulating fast dynamic problems and taking into account fluid/structure interaction.

DIVA3D/LS-DYNA interface

The process is outlined below:

- performance of many DIVA3D calculations covering the worst situations in terms of filling ratio and excitation motions, the wall being considered as rigid;
- selection of a few impact cases as the most violent ones according to DIVA3D post-processing tools based on local kinetic energy calculations or impact pressure assessment with acoustic pressure approximation;
- for each of the specially selected impacts, data transmission of the complete flow in the tank at one instant just before the first contact between liquid and structure, from DIVA3D database to the F.E. model for the explicit code;
- for each of the selected impacts, performance of the explicit F.E. calculations (flow prediction, fluid/structure interaction, structural response) taking into account the kinematic conditions imposed to the tank. The simulations last until the stress waves are sufficiently dumped. It means generally about 0.1 s.

The F.E. explicit software which has been chosen is LS-DYNA [Ref 7]. This code, very well known in car industries, is developed by LSTC in Livermore (U.S.A). It has been already used at IRCN for addressing ship collision problems. The development of the interface between DIVA3D and LS-DYNA has been entrusted to DYNALIS, the French distributor of LS-DYNA.

A first version of the interface is under testing. It is based essentially on the following choices concerning the LS-DYNA model:

- Lagrangian F.E. formulation for the tank structure;

- Eulerian F.E. formulation for the fluid described with two materials (liquid + gas);

- each fluid finite element is characterized by one density, one dynamic viscosity and one internal energy volumic density. The fluid behaviour follows a polynomial equation of state relating its pressure to its internal energy.

The main functions of the interface are:

- reading of the complete database of DIVA3D;

- building of a preliminary Eulerian grid for LS-DYNA which the fluid and structure models will move through;

- building of a preliminary structural model of the tank with rigid walls ;

- initialization of the LS-DYNA fluid model from the data of the DIVA3D fluid model at an instant t_0 selected interactively by the user ;

- calculation of the inertial forces at each node of the LS-DYNA F.E. model at the time t_0. In this first version of the interface, these initial forces are considered as constant during the impact simulation. (The impact simulation lasts about 0.1 s while the period of the ship motion is of the order of 10 s).

Afterwards, the user has to carry out the refined F.E. model of the structure area directly concerned with the impact and to integrate it in the previous simplified model.

Treatment of an academic case

The tank considered is parallelepipedic, the dimensions of which are 30 x 30 x 21 m. It is filled with 50% of water and 50% of air and forced to rotate around a diagonal axis $(\vec{x}+\vec{y})$ with a harmonic motion. The period of the rotation is T = 6 s which corresponds to the natural period of the liquid either along x axis or y axis. The amplitude of the forced rotation is a = 10°.

This forced excitation will lead to sloshing impacts on the tank ceiling. One of these impacts will be studied considering the ceiling as an elastoplastic 5 mm steel plate, the other parts being considered as rigid.

The liquid motions were simulated by DIVA3D. The fluid model is a parallelepipedic box 20 x 20 x 14 finite volume meshing.

As it was foreseen (all was done for that !), violent impacts occur successively in the upper corners located symmetrically in relation to the rotation axis. The impact selected to be specifically studied by LS-DYNA occurs at $t \approx 8.25$ s with a velocity close to 30 m/s (Fig.5-1).

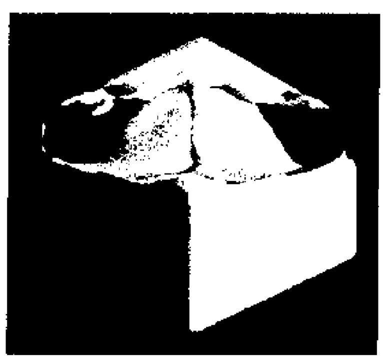
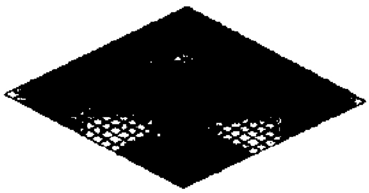
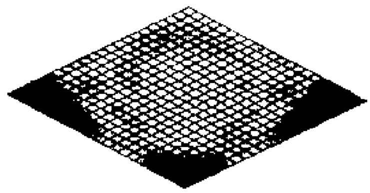
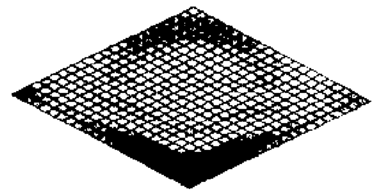


Fig.5-1 Free surface at t = 8.25 s (just before the impact) as simulated by DIVA3D
The studied impact is located in the foreground of the figure

The flow data, as simulated by DIVA3D, were transmitted in the adequate form to LS-DYNA at t = 8.25 s (just before the studied impact) thanks to the above mentionned interface.

LS-DYNA3D simulated then the flow, the fluid/structure interaction from the 1st contact time and the structural response of the elastoplastic ceiling under the impact load.

During the 10^{-3} s following the first contact two stress waves are propagated through the ceiling from the upper corner to the two opposite sides of the square (along the edges) and then reflected.

Propagation of the two stress waves (Von Mises stresses)

Fig.5-2 : $t = 0.1\ 10^{-3}$ s **Fig.5-3** : $t = 0.6\ 10^{-3}$ s **Fig.5-4** : $t = 1.1\ 10^{-3}$ s

The deformation becomes significant only as the two reflected waves meet again (Fig.5-4).

One second phase starts then during which the corner is progressively deformed (Fig.5-5) This second phase lasts about 0.1 s and seems to correspond to the quasi-static response of the elasto-plastic ceiling.

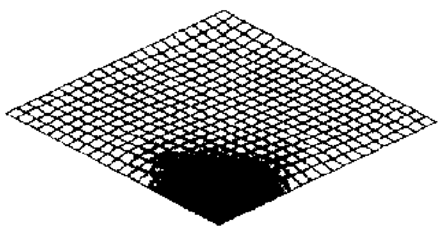


Fig.5-5: Maximum deformation of the ceiling after impact

Conclusion

As shown by the validation results, the DIVA 3D software provides to the designer a valuable new tool for sloshing risk analysis in 3D conditions.

The selected mathematical formulation, associated with computer capabilities now common in design offices allows to simulate precisely the liquid motions in a complex tank submitted to real ship excitations.

The computer results allow to determine the more loaded structural parts and also the liquid velocity field.

It is therefore possible to analyze the influence of changes of parameters such as tank shapes or dimensions, but also navigation conditions which influence the excitation periods or amplitudes.

In addition, the access to the internal liquid velocity allows to calculate the loads on internal elements such as pump support towers or swash bulkhead in view to optimize scantling.

The simulation of real model tests and the application on real cases of ships at sea, mainly LNG carriers, provided a serious validation and the demonstration of the validity of the method and tools to shipbuilding.

The next step, yet under progress, is the calculation of the structural response with full interaction between liquid and flexible wall. This approach will solve the non physical meaning of the impact pressure which often leads designers to erroneous interpretations.

The presented first results are very encourageous and one can consider that a practical solution for design offices will be available soon.

Sure that the future FPSO developments will take advantage of this new tool.

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A HYBRID AGENT APPROACH FOR SET-BASED CONCEPTUAL SHIP DESIGN

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Abstract

Advanced marine design, particularly in the United States, advocates the use of cross-functional design teams, or Integrated Product Teams (IPT's), who will undertake a concurrent engineering approach to all phases of ship design. Further, the study of the world-class Toyota automotive design process has highlighted the potential of a set-based design approach in concurrent engineering to provide a greater probability of achieving a global optimum for the overall design. A hybrid human-computer agent approach is introduced to facilitate set-based conceptual ship design by a cross-functional team of naval architects and marine engineers. The disciplinary/technical specialists are organized and tasked as agents within a design network that can be either be co-located or interconnected across the web. Computer agents are introduced between each pair of human design agents to facilitate their communication and negotiation. A systematic market approach, developed in the Defense Advance Research Projects Agency (DARPA) sponsored Responsible Agents for Product-Process Integrated Design (RAPPID) project, was utilized as an initial approach to facilitate this team, set-based design. The conceptual design of a hatch-covered, cellular, feeder container ship was undertaken by a team of student design agents to assess the effectiveness of this design approach. The design process converged within one seven-hour design session indicating the promise of a hybrid agent approach in future marine conceptual design efforts.

Introduction

The conceptual design of ships is an exemplar of complex early stage design in which a wide range of technical, physical, and economic issues must be considered and balanced to achieve an optimum design. This design problem is constrained by multiple, interacting physical and technical constraints. Efforts to use formal optimization in this context whether classical nonlinear programming, multidisciplinary nonlinear programming (MDO), goal programming, or genetic algorithms have generally not proven to be of significant practical value. This occurs because the mathematical models compatible with these numerical methods must necessarily simplify and constrain the problem to such a degree that important real considerations and issues are lost.

Advanced design in the United States has begun to emphasize the use of a multidisciplinary team-based concurrent engineering approach. Notable initial successes have been in the automotive (Chrysler Viper, Ford Mustang) and aircraft industries (Boeing 777). Integrated Product Teams (IPT's) are advocated for future naval ship design (1). Core cross-functional design teams are co-located or linked in a virtual environment to perform the overall design task. The human designers as a cross-functional team are able to comprehend, process, and negotiate the complex range of issues and constraints relevant to a particular design. Advanced simulation-based design (SBD) techniques are also being developed to provide the designers with faster and more reliable results describing the physical performance and manufacture of the design. In these advanced design environments, the ability of the designers to communicate and negotiate about the design decisions needed to reach a globally optimum design will likely become a limiting factor.

Team-Based Concurrent Engineering Design

There is a move toward the use of team-based concurrent engineering within ship design in the United States. Notable initial studies have been undertaken by Bennett and Lamb as part of the National Shipbuilding Research Program (2) and by Keane and Tibbitts within the U. S. Navy ship design community (1). Whether labeled Integrated Product Process Design (IPPD) teams or Integrated

Product Teams (IPT's), these teams seek to bring together at the earliest stages of design representatives of engineering, manufacturing, marketing, training, life-cycle support, operations, purchasing, suppliers, etc. to consider concurrently all aspects of the ship's life-cycle so that a global optimum can be approached. The U.S. Navy is currently emphasizing the minimization of total ownership costs. A commercial venture might seek to minimize the Required Freight Rate (RFR). The Shipbuilding Policy/Build Strategy approach to ship design and production advocates that many concurrent engineering considerations be resolved in developing a standard approach to designing a given class of vessels and in rationalizing the production system of the shipyard in advance of developing a specific design (3, 4).

These concurrent engineering design teams are usually co-located, but will also be brought together virtually over the Internet in the future. The ability of these teams to communicate and negotiate design tradeoffs and decisions is a critical factor in the design process.

Traditional Point-Based Ship Design

The traditional approach to communicating the initial ship design process has utilized the "design spiral" since this model was first articulated in the 1959 (5). This model emphasizes that many design issues of resistance, weight, volume, stability, trim, etc interact and these can be considered in sequence, in increasing detail in each pass around the spiral, until a single design which satisfies all constraints and balances all considerations is reached. This approach to design can be classed a point-based design since it is seeking to reach a single point in the design space. The result is a base design that can be developed further or used as the start point for various tradeoff studies. A disadvantage of this approach is that while it produces a feasible design it may not produce a global optimum.

Set-Based Design

The design and production of automobiles by Toyota is generally considered world-class and it is, thus, subjected to considerable study. The study of the Toyota production system led to the evolution of the conceptualization of Lean Manufacturing (6). The Japanese Technology Management Program sponsored by the Air Force Office of Scientific Research at the University of Michigan has more recently studied the Toyota approach to automobile design (7, 8). This process produces world-class designs in a significantly shorter time than other automobile manufacturers. The main features of this design process include:

- broad sets for design parameters are defined to allow concurrent design to begin,
- these sets are kept open longer than typical to more fully define tradeoff information,
- the sets are gradually narrowed until a more global optimum is revealed and refined.

This approach is illustrated in a sketch produced by a Toyota manager in Fig. 1. Alan Ward has characterized this design approach as set-based design. It is in contrast to point-based design or the common systems engineering approach where critical interfaces are defined by precise specifications early in the design so that sub-system development can proceed. Often these interfaces must be defined, and thus constrained, long before the needed tradeoff information is available inevitably resulting in a sub-optimal overall design. A simple example is the competition between an audio system and a heating system for volume under the dashboard of a car. Rather than specify in advance the envelope into which each vendor's design must fit, they can each design a range of options within broad sets so that the design team can see the differences in performance and cost that might result in tradeoffs in volume and shape between these two competing items.

The set-based design approach has a parallel in the Method of Controlled Convergence conceptual design approach advocated by Stuart Pugh (9).

A Hybrid Agent Approach to Design

Agents are elements of computer code with elements of perception, intelligence, and adaptability capable of taking independent action. This is in contrast to earlier functions and subroutines that have a programmed function and are called by code to perform that task. This is also in contrast to objects that have persistent data and functionality and can be instantiated within code to carryout these tasks. In a network simple agents can each perform their specific, assigned task and an overall result can emerge from the interactions of the group of agents. Agents can observe system activities and act when necessary.

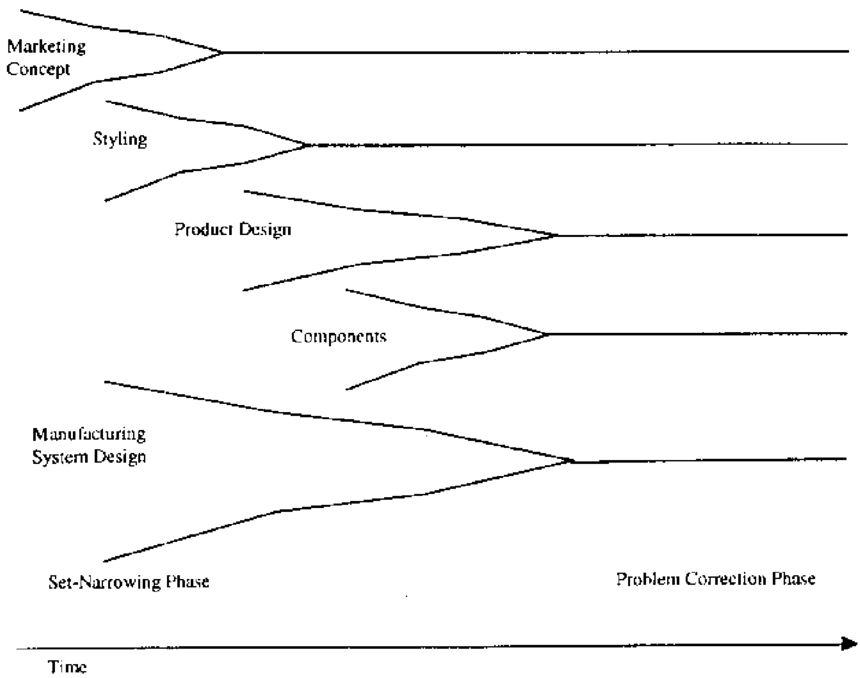

Figure 1. Parallel Set Narrowing Process Sketched by a Toyota Manager (8)

In this work, a hybrid agent approach is utilized. It is felt that problems as complex as ship design will continue to require the expertise, perception, and judgement of the human designers. Using an agent model, however, these designers can be organized and tasked as a network of agents based upon their technical specialty or particular role. Further, computer agents can be introduced between each pair of design agents to facilitate their critical communication and negotiation about the design. This concept results in a hybrid network of human and computer agents.

In the remainder of this paper, the design task of interest is the preliminary, parametric, bid-response design for a feeder container ship. The design team has developed basic design standards and the approach for the design and arrangement of feeder container vessels in the range that their company intends to compete through the development of their Shipbuilding Policy and Build Strategy elements. The shipyard has received a brief performance specification designating the capacity and a speed of the vessel indicated by the owner's transportation studies. The goal is to provide a preliminary sizing of a vessel that will provide this function at minimum RFR. In the following, the organization of a design team as a network of agents, a systematic market approach for design negotiation, and the function of the computer agents are described. An initial experiment using this approach is then summarized.

Agent Definition

The naval architects and marine engineers in a preliminary design team can be assigned specific task as agents within a design network. The negotiation mechanism to be used in this example involves a systematic market economy in which design parameters are bought and sold in specific markets. The designers express their desires through their bid or utility functions and trade in dollars that allow all parameters to be valued on a common basis. The task of interest is the parameter stage preliminary design of a vessel for which the shipyard must respond with a bid. The design team is brought together for a day to size the vessel and establish the basis for the bid response. The design agents are each tasked with a portion of the design process and provided with design tools and data to support this work.

The overall network of design agents is shown in Fig. 2. Seven design agents are utilized in this initial investigation. The Chief Engineer, at the upper right, acts as the Voice of the Customer and buys performance parameters from the other agents. In this case, four performance parameters are utilized: the service speed V_k of the vessel on trials at 85% Maximum Continuous Rating of the machinery, the TEU capacity of the vessel, the transverse GM_t as a measure of initial stability, and Clarke's Turning Index P_C as a measure of vessel turnability (10). Other performance characteristics could obviously be included. An implied eighth agent, at the lower left, is the Shipbuilder or the shipyard Production Department which will provide the vessel at a total ship capital cost that is the total of the machinery related cost C_m, the structure related cost C_s, and the outfit related cost C_o. These are implemented through capital cost estimation equations included in the design process. The RFR being optimized by the Chief Engineer includes operating costs, so there are also implied markets for the machinery related operating costs Cop_m and the remaining operating costs Cop_r required by the ship design.

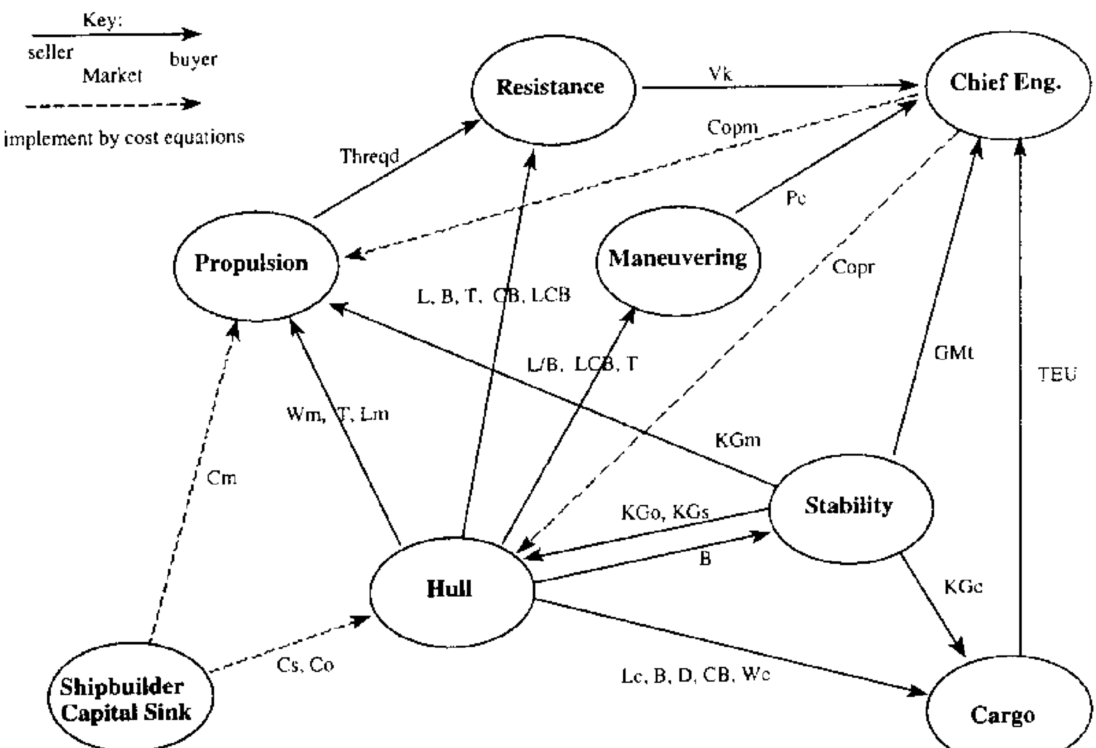

Figure 2. Agent Interaction Diagram

Definition of Conceptual Design Agents

As shown in Fig. 2, the design agents are defined in two hierarchical levels. Four agents are responsible for providing the performance parameters to the Chief Engineer; i.e., Resistance provides speed, Maneuvering provides turnability, Stability provides GM_t, and the Cargo agent provides the TEU capacity. The two agents in the second tier provide the machinery and propulsor needed to provide the total propeller thrust required by the Resistance agent and provide the overall hull needed to meet the needs of the design. The seven design agents are defined in detail in Table 1, which lists the design role or objective and constraint responsibility of each agent. It also lists the parameters that each agent buys or sells. The agent with the greatest at stake with respect to the associated constraints is the seller of the particular parameter. The agents are each tasked to act altruistically so that no profit is made; i.e., sell revenues balance the buy obligations to the other agents. The parametric design tools provided to each agent are also listed.

The Chief Engineer agent is the overall leader of the design team and serves as the Voice of the Customer. He or she seeks a minimum RFR design (as opposed to a minimum cost design that would more typically be the shipyard's objective in developing a bid response). The computational tool available is a RFR calculation based upon the parameters of the design.

The Resistance agent is responsible for satisfying the hydrodynamics physics and sells service speed to the Chief Engineer. To achieve this speed, this agent must buy total propeller thrust from the Propulsion agent, but can also participate in the markets for the hull parameters that will affect the required thrust; i.e., length, beam, draft, block coefficient, and longitudinal center of buoyancy. The computation tool available is the Power Prediction Program (PPP) which implements Holtrop and Mennen's regression-based resistance prediction method for displacement hulls (11, 12, 13).

The Maneuvering agent is responsible to provide turnability to the Chief Engineer and decide whether or not to include a bow thruster in the design. To provide turnability, the agent sizes the rudder based upon a parametric model related to ship draft and participates in the markets which will affect the maneuverability; i.e., length/beam ratio, longitudinal center of buoyancy, and draft. The computational tool available is the Maneuvering Prediction Program (MPP) which implements and extends the work of Clarke et al (10, 11).

The Stability agent is responsible for ensuring that the vessel provides the minimum GM_t required by the Chief Engineer. To provide this stability, the agent must buy beam from the Hull agent using revenues acquired by selling vertical centers of gravity to the Cargo, Propulsion, and Hull agents. The computational tool available incorporates preliminary weights and centers estimation models from Watson and Gilfillan (14) and Kupras (15) into a transverse weight summation spreadsheet.

The Cargo agent is responsible for ensuring that the vessel provides the TEU capacity required by the Chief Engineer. To provide this, the agent must buy cargo box length L_c, beam, depth, block coefficient, and cargo weight from the Hull agent and buy cargo vertical center of gravity from the Stability agent. The design tools available are a matrix or catalog of cargo box dimensions for various choices of container configuration within the hold and on deck above the hatch covers assuming a prismatic hull with two containers missing in each stack at the lower corners. This agent also has a parametric regression model (or alternatively an Artificial Neural Network) for the total TEU capacity that reflects the full tapering effect of the hull on the container block.

The Propulsion agent is responsible to provide the propulsion machinery necessary to produce the total propeller thrust required by the Resistance agent. The agent must buy machinery box length L_m, draft (influencing propeller diameter), and machinery related weight and vertical center of gravity. Implied markets include the capital purchase of the machinery and the machinery related operating costs. The design tools available are a catalog of MAN B&W and Wartsilla medium-speed diesels and the Propeller Optimization Program (POP) which uses the Nelder and Mead Simplex Search and External Penalty Function (16) to design the optimum Wageningen B-Screw Series propeller subject to diameter and cavitation constraints (11, 17). With the overall workload assigned to this agent, he/she is supported by a propeller design assistant.

The Hull agent is responsible for the overall integration of the hull dimensions and arrangement and for ensuring that the total weight equals the displacement. This agent is the seller in all of the hull sizing and weights markets. The Hull agent must also buy the vertical center of gravity of the structure and outfit he/she will provide. Implied markets include the capital purchase of the structure and outfit portions of the ship and the non-machinery related operating costs. The provided computational tool incorporates preliminary weights and centers estimation models into a longitudinal weight summation spreadsheet. With the overall workload assigned to this agent, he/she is supported by an arrangements design assistant.

Table 1. Definition of Design Agents

Agent: Chief Engineer; Voice of the Customer	
Objective:	Provide functional requirements to customer at minimum Required Freight Rate
Buys:	V_k, P_c, GM_t, and TEU
Sells:	Cop_m, Cop_r (implemented through equations in RFR calculation)
Constraints:	customer's functional requirements
Tools:	RFR calculation
Agent: Resistance	
Objective:	Provide required ship speed
Buys:	L, L/B, T, C_B, LCB, and Th_{reqd}
Sells:	V_k
Constraints:	hydrodynamics
Tools:	Power Prediction Program (PPP)
Agent: Maneuvering	
Objective:	Provide required turning capability; set rudder/thruster size
Buys:	L/B, LCB, and T
Sells:	Clarke's Turning Index P_c
Constraints:	horizontal plane maneuvering dynamics
Tools:	Maneuvering Prediction Program (MPP)
Agent: Stability	
Objective:	provide required initial transverse stability
Buys:	B
Sells:	GM_t, KG_m, KG_o, KG_s, and KG_c
Constraints:	transverse equilibrium
Tools:	transverse portion of Weights I summary
Agent: Cargo	
Objective:	provide required TEU/FEU capacity
Buys:	L_c, B, D, C_B, W_c, and KG_c
Sells:	TEU
Constraints:	cargo block geometry
Tools:	cargo block catalog; TEU capacity model that includes the effects of longitudinal hull taper
Agent: Propulsion	
Objective:	provide required propeller thrust; choose engine; design propeller
Buys:	L_m, W_m, T, and KG_m plus C_m and Cop_m (implemented through equations in RFR calculation)
Sells:	Th_{reqd}
Constraints:	propeller hydrodynamics, available Wartsilla and MAN B&W medium speed diesels
Tools:	engine catalogs, Propeller Opt. Program (POP); supported by propeller designer
Agent: Hull	
Objective:	Provide required hull volume and required outfit; ensure even keel
Buys:	C_s, C_o, Cop_r (implemented through equations in RFR calculation)
Sells:	L, L/B, B, T, D, C_B, LCB, W_m, and W_c
Constraints:	Archimedes Principle, zero trim
Tools:	longitudinal portion of Weights I summary; supported by ship profile manager
Agent: Shipbuilder/Capital Sink	
Objective:	provide specified vessel to design agents
Buys:	nothing
Sells:	vessel for price that is the sum of C_m, C_s, and C_o
Constraints:	sink
Tools:	building cost estimating equations; implemented directly in RFR calculation

Market and Auxiliary Variables

The work of the agents requires that the market parameters be precisely defined in advance. Each agent also needs to know the value for additional auxiliary variables in order to carryout needed computations and analyses. The choice of these auxiliary variables is the responsibility of specific agents based upon their design decisions or the results of design computations that they perform. The auxiliary variables are not part of the markets, but must be defined and communicated to other agents as needed. The definition of the market variables and the information flow of the auxiliary variables among agents are summarized in Table 2.

Systematic Markets and RAPPID

A designer seeks to embed a set of *functions* in an object with specified *characteristics* (e.g., weight, materials, power consumption, and size). Conflicts arise when designers disagree on the relation and importance of the characteristics of their own functional pieces and the characteristics of the entire product. There is no disciplined way to tradeoff characteristics such as weight and power consumption against one another. The problem is the classic dilemma of multivariate optimization. Analytical solutions are available only in specialized niches. As a result, the state of current practice is that tradeoffs are resolved in ways that do not always optimize for the best overall system and manufacturability

The Responsible Agents for Product/Process Integrated Development (RAPPID) project developed an approach to design that helps human designers manage product characteristics across different functions and stages in the product life cycle (18, 19). These agents participate in a design *marketplace* where the goods being traded represent the design characteristics of each of the product components. By representing the explicit cost and value of these design characteristics in a common currency, the resulting marketplace provides a self-organizing dynamic that may yield more rational designs faster than conventional techniques. These markets allow individual designers to make tradeoffs and narrow sets of design characteristics in a way that leads to better global designs.

RAPPID addresses three core problems in design:

- *Planning*. Design tasks cannot be sequenced in detail. There is generally no way to progress through the design analysis and decision-making in an organized way such that all the information is available when necessary to each designer. Thus, the design spiral.
- *Coupling*. Designers think locally, but they are tightly coupled with other designers. Decisions that one designer makes affect the decisions that other designers have made. This constant need for re-evaluation as a result of changes at the design interfaces can lead to lengthy cycles of iteration and change.
- *Prioritizing*. Designers have no common language for comparing the importance of issues.

In RAPPID, independent agents use set-based reasoning in a design marketplace to address these problems as depicted in Fig. 3. The combination of independent agents (designers) working with set-based reasoning addresses the planning issue. By working with sets or ranges of parameters, designers can work in parallel without waiting for other designers to set the value of some design characteristic they need. Markets provide the means by which many alternatives in a set can be evaluated using a common currency for the comparison. And finally, the RAPPID markets provide information to each designer that allows them to make individual decisions that contribute to globally optimal results much as real markets work to find the best clearing price for a good.

RAPPID Markets

Figure 1 shows an example of agents used in a preliminary ship design and the design characteristics that they trade. One can think of this network as a supply chain. The Propulsion agent sells the required thrust (Th_{reqd}) to the Resistance agent. The Resistance agent buys the amount of thrust it needs from the Propulsion agent as well as aspects of the hull shape which affect resistance from the Hull agent in order to produce the service speed (V_k) the Chief Engineer agent seeks. The arrows in the diagram indicate the direction of the sale and the label identifies the market good or design characteristic.

In RAPPID buyers express their preference for an item they are purchasing using a qualitative cost curve. The curve expresses the range of prices the buyer is willing to pay for a set of values of a design characteristic. The curve also expresses in general how this preference varies over the range of the design characteristic. The ^ shaped curve in Fig. 4 is an example of a buyer's buy curve. In this example, the buyer is indicating that they would be willing to pay between $100K and

Table 2. Variable Mapping Among Design Agents

Agent Tool	Variable	Units	Description	Chief Engin./ Customer	Resistance PPP resistance	Maneuvering MPP maneuvering	Stability Weights I trans. intact stab	Cargo TEU model cargo layout	Propulsion POP, catelog prop., engine	Hull Weights I longl. sizing, trim
Market Variables	Vk	knots	trials speed at (1-service margin) power	B	S	X			X	X
	Pc		Clarke's turning index	B		S				
	GMt	m	transverse metacentric height	B			S			
	KGm	m	machinery related VCG				S		b	
	KGc	m	cargo VCG				S	B		
	KGo	m	outfit VCG				S			B
	KGs	m	structure VCG				S			B
	TEU		20' container count	B				S		
	Threqd	kN	total required propeller thrust		B				S	
	L	m	LWL, waterline length	X	B	X	X			S
	L/B		length/beam ratio		B	B				S
	T	m	mean designed draft		B	B	X		B	S
	CB		block coefficient	X	B	X	X	B		S
	B	m	beam	X	X		B	B	X	S
	Wm	tonnes	propulsion machinery, fuel, lube oil weight				X		B	S
	Lm	m	length of engine room						B	S
	Lc	m	length of cargo box					B		S
	D	m	depth	X	X			B	X	S
	Wc	tonnes	cargo weight				X	B		S
Auxiliary Variables	w		mean longitudinal wake fraction		O				X	
	t		thrust deduction		O				X	
	etar		relative rotative efficiency		O				X	
	Ar	m^2	rudder plan area		X	O				
	BThr	kN	bow thruster thrust	X	X	O				
	Ncrew		complement	X			O			X
	Ndays		endurance days for stores and water				O			X
	KB	m	vertical center of buoyancy				O			X
	design KG	m	ship vertical center of gravity including margins				O			X
	hdb	m	double bottom height					O	X	
	sfc	t/kWhr	propulsion specific fuel consumption	X					O	
	sloc	t/kWhr	propulsion specific lube oil consumption	X					O	
	no. props.		number of propellers		X	X			O	X
	Dp	m	propeller diameter						O	
	Pb	kW	main engine Maximum Continuous Rating	X					O	
	Cx		maximum section coefficient		X					O
	Cwp		waterplane coefficient		X		X			O
	LCB (=LCG)	%L,+fwd	longitudinal center of buoyancy		X	X				O
	Wo	tonnes	outfit weight				X			O
	Ws	tonnes	structure weight				X			O
	LBP	m	length between perpendiculars	X						O
	DWT	tonnes	total deadweight	X						O
Implied Market Variables (implemented by cost in RFR calculation in the initial experiment)	Cm	M$	machinery related capital cost	X					O	
	Cop,m	M$/yr	machinery related operating costs	X					O	
	Co	M$	outfit related capital cost	X						O
	Cs	M$	structures related capital cost	X						O
	Cop,r	M$/yr	remainder of operating costs	X						O

Key:
X = input
B = buyer
S = seller
O = output

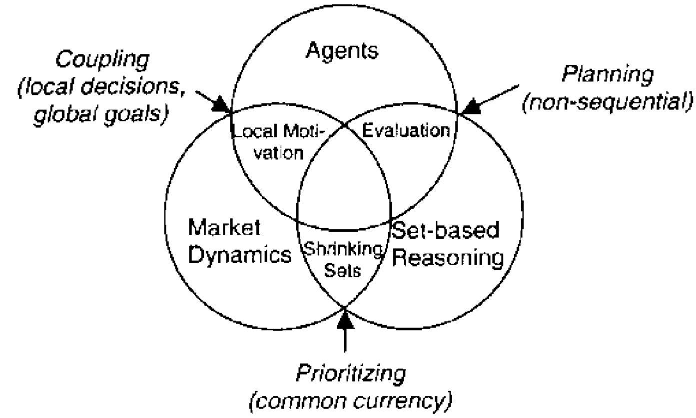

Figure 3. Interaction of Three Concepts in RAPPID

$500K for thrust in the range of 600 to 1600 kN. In general, thrust is considered more valuable towards the middle of that range than at the ends. Similarly, the supplier can issue a sell bid (superimposed on the buy bid in Fig. 4). The supplier indicates thrust in the range of 600 to 1600 kN ranges in price from $100K to $450K and, in general, its price increases as thrust increases.

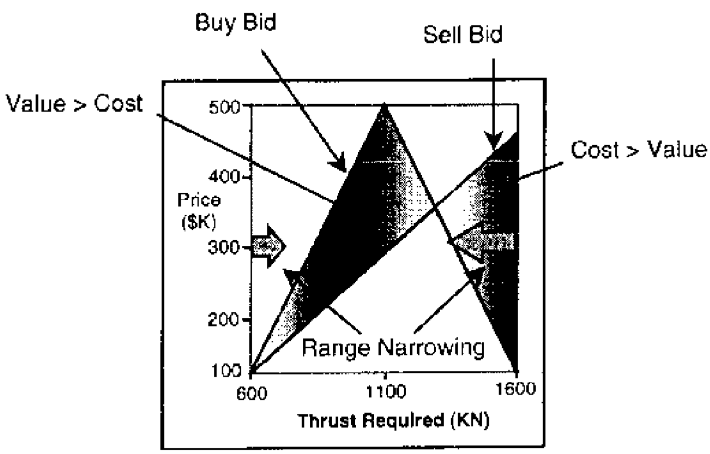

Figure 4. Buy and Sell Bid Curves

Based on this qualitative information, the buyer can begin to make some choices. The ideal thrust would be the point where the difference between the buy and the sell price curves is maximized. This is the thrust that would provide the most value to the buyer for the least price. Since these curves are only qualitative, we cannot identify that thrust value directly from these bids. However, one can say that at the high end of the thrust range, the price is most likely much higher than the customer is willing to pay (Cost > Value). It is also unlikely that there is a suitable thrust at that end of the range, so the customer can narrow the range down from the high end. One could also remove a small amount from the low end of the range knowing that the maximum difference between buy and sell curves is unlikely to be found at the low end. Once the range is narrowed, the customer and buyer can spend more time analyzing a much narrower range of options. This will result in new bids and possibly new curve shapes. As certain ranges are narrowed down, other ranges will also narrow as a result. Many design characteristics are coupled together so that a compression of one range will cause other ranges to narrow throughout the network. Eventually these ranges will narrow to a single point. At that point, the design is complete. In RAPPID no money actually changes hands. The buy and sell curves are used as approximations of cost and preference surfaces to guide the designers in searching for an optimal location in the design space. The use of these qualitative market dynamics in RAPPID is based on research in market-based distributed constraint optimization (20).

RAPPID Market Server

To assist designers in making buy and sell bids and analyzing the market data for places to narrow ranges, a RAPPID Market Server as shown schematically in Fig. 5 was created. The market server was designed to work in a wide variety of design environments. It is intended as a tool to assist a distributed team of designers in analyzing their design space, making appropriate tradeoffs, and managing the convergence of the design around the final solution. The design histories that it maintains provide a detailed transaction log that can be used to reconstruct the rationale used to make various tradeoffs.

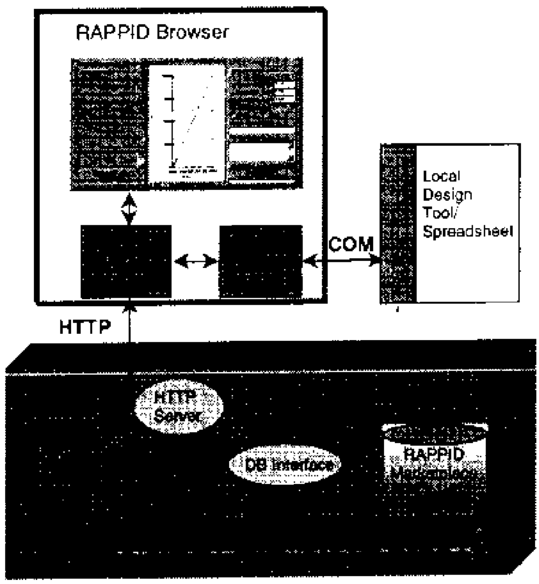

Figure 5. RAPPID Design Market Server

The market server consists of a database server that is accessed through a web interface. The database defines all the markets and the agents and keeps records of all the market transactions. The main web page market summary view (not shown) displays all the current markets and the last buy and sell bids. This provides the designers with a quick view of the state of all the markets. One can quickly identify from this view markets which show the greatest potential for narrowing or which might be the most profitable upon which to work.

Detailed information on any individual market is available through a Java applet an example of which is shown Fig. 6. The applet shows the last buy bid for the market in a form on the left. The form on the right details the last sell bid. A simple graph of the two bids is displayed in the middle. The graph provides a visual clue to the designers of how to narrow the ranges to reach the point of greatest value for least cost. If the agent is registered as a bidder in the market, then one of the forms will have editable fields where new bid information can be submitted. The bid includes a small Notes field where the designer can send explanatory information regarding the bid or reference supporting documents.

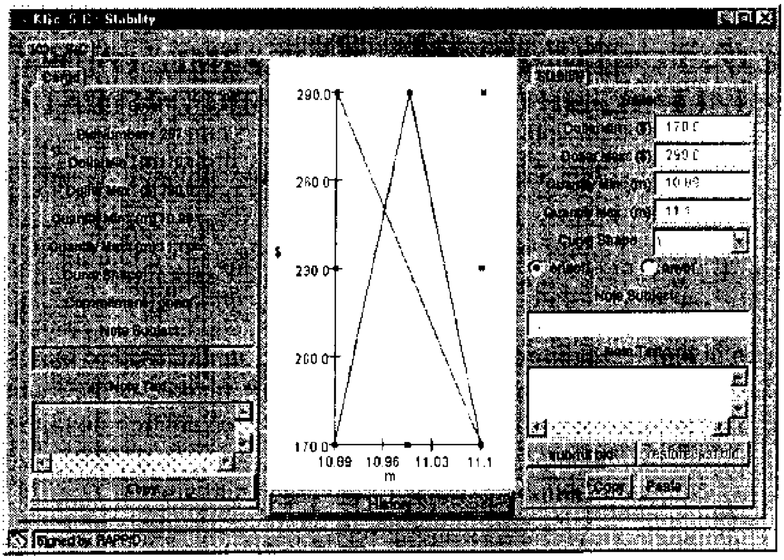

Figure 6. Java Applet for Market Bids

Since designers use many different tools to analyze their design, the RAPPID Market Server is designed to interface through a wide range of standard methods, from the simple clipboard to more powerful DCOM and CORBA interfaces. This relieves the designer of the burden of manually transferring data between the market server and their design tools.

Hybrid Agent Ship Design Experiment

The Hybrid Agent Ship Design Experiment was conducted in two phases: an initial exploratory experiment and then the more formal Hybrid Agent Experiment.

Initial Exploratory Experiment

The initial exploratory phase was completed in April 1998. This involved the initial evaluation of the agent concept as a possible approach to preliminary ship design without the use of systematic markets to aid design negotiation. The initial experiment was performed by seven University of Michigan undergraduate naval architecture students using the Undergraduate Marine Design Laboratory of the Department of Naval Architecture and Marine Engineering. The assigned task was, given a set of owner's requirements, to produce a conceptual design of a feeder container ship with the lowest RFR within four hours using a prototype web-based agent communication environment.

The Phase 1 experiment provided a template for the development of the Phase 2 experiment. From the results of the initial experiment, the original agents, their tasks, and their design tools where redefined. The RAPPID systematic market approach was added to experiment with the hybrid agent approach to aid design negotiation. It became clear that each agent's role needed to be well defined using market and auxiliary variables unique with respect to the specific role of the each agent. This can be seen in the variable length. The total ship length is an important variable to many agents. It was found that the agents could be more effective, however, if they were concerned only with that portion of the total length that they could clearly define. Thus, the ship length was broken down into Length of Engine Room, Length of Cargo Box, and total LWL for use by different agents.

Another important conclusion from the Phase 1 experiment was that the workload and level of design analysis sophistication assigned to each agent needed to be balanced across the agents. The original experiment had agents with widely varying workloads and levels of design/analysis complexity. This caused delays in the process since some agents had large amounts of data to analyze while other agents had very little work to do. The act of overwhelming an agent caused that agent to breakdown, thus, hindering the whole process.

Hybrid Agent Design Experiment

In January of 1999, the Phase 2 experiments began. The Center for Electronic Commerce of the Environmental Research of Michigan (ERIM) joined the experiment to adapt its RAPPID systematic markets software to this design problem. The Phase 2 experiments consisted of an initial RAPPID and design software training day, January 16, 1999, and a final experiment day, January 30, 1999. The initial training day was used to help familiarize the design team with the agent-based and set-based design concepts and software environment. The time between the training day the experiment day allowed the individual designers to become more familiar with their particular agent role as well as the RAPPID software. The students in the second experiment were all graduate students with one exception. The Undergraduate Marine Design Laboratory was again used.

The Phase 2 design experiment had essentially the same design goal as the Phase 1 experiment. The primary requirements for the Hybrid Agent experiment where for the students to respond to a request for bid for a conventional hatch-covered, handy-sized feeder cellular container ship for use along the Pacific Northwest feeding to the container terminals in Oakland, CA, and Seattle, WA. The vessel needed to satisfy the following requirements:

- Carriage of 500 TEU (Twenty foot Equivalent Unit) with an average weight of 15.0 tonnes with a VCG at 45% of the container height. Uniform loading.
- Alternative 250 FEU (Forty foot Equivalent Unit) with an average weight of 20.0 tonnes.
- Endurance of 1600 nm at service speed for fuel, and 20 days for provisions and water
- Maximum length and beam Panamax; maximum draft of 6.0 m.
- Service speed at 85% Maximum Continuous Rating on trials of 16.5 knots.
- Clarke's Turning Index of at least 0.35.
- Minimum GM_T of at least 0.25 m in the uniform load condition.

To establish starting sets for the primary ship dimensions at the beginning of the experiment, regression equations where used to estimate LBP, B, D, and T as a function of TEU and ship speed. The mean value produced by the regression equations $\pm 2\sigma$ (regression Standard Errors), which is expected to contain 95.5% of the world fleet, was used as the initial set. The initial sets for the primary size variables allowed the agents to begin their particular evaluations. These initial sets can be seen in Table 3.

Table 3. Initial Set Ranges for Primary Size Variables

Variable	Lower Bound	Upper Bound
LBP	100.9 m	149.5 m
LWL	103.9 m	152.9 m
B	16.8 m	24.0 m
D	7.8 m	13.7 m
T	2.6 m	7.4 m

The design experiment was conducted over a period of about seven hours during which the primary variables converged to a final design sizing. This convergence for the LWL sets considered in the negotiation between the Hull agent and the Resistance agent is illustrated in Fig. 7.

Table 4 is the relevant portion of the cargo box geometry spreadsheet used by the Cargo agent. The sheet shows the beam, depth, length of cargo box, container configuration, and total number of containers for a given configuration and length ignoring the effect of the longitudinal taper of the hull. The table has several differently shaded regions that show the convergence of the design during the experiment. The design sets initially included three cargo box lengths, three beams, and three depths. The non-shaded region shows the near final set of cargo configurations.

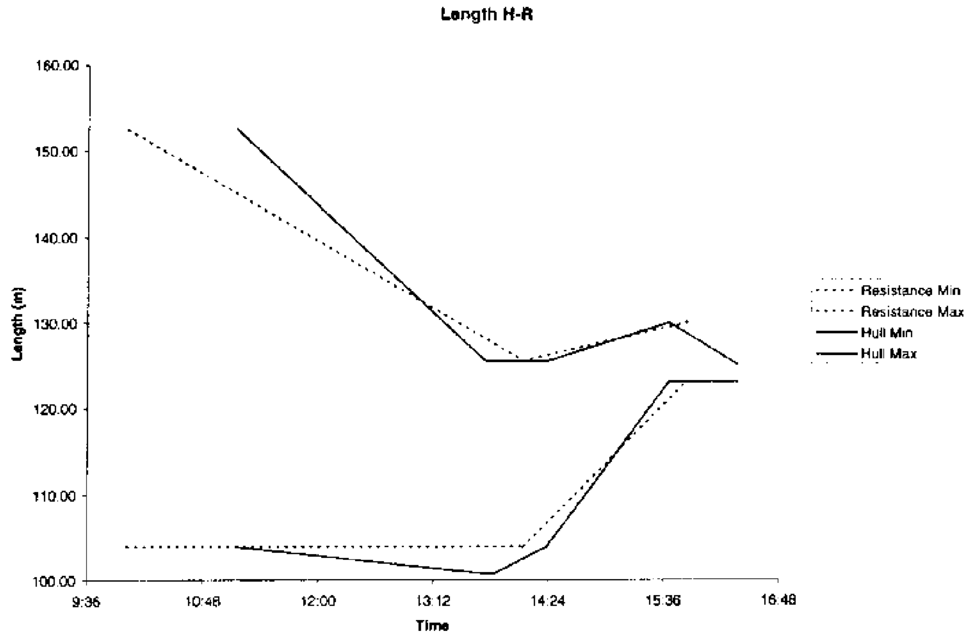

Figure 7. Convergence of Length Market Over Time

The near final set consisted of one beam (22.2 m), two depths (9.96 m and 12.55 m), and two cargo box lengths (69.4 m and 82.92 m). The longer hull was then eliminated since it would provide excessive TEU capacity. Required Freight Rate consideration by the Chief Engineer agent then reduced the set further by eliminating the larger depth so that the design team converged to a beam of 22.2 m, depth of 9.96 m, and a cargo box length of 69.4 m.

Conclusions

A hybrid system of human design agents and intermediate computer agents that can facilitate their communication and design negotiation shows promise as a means of achieving effective conceptual ship design by cross-functional design teams. This fosters a set-based design approach to conceptual ship design. The following specific conclusions are noted:

- The network of agents provides an effective way to organize a cross-functional teams.
- The negotiation across the network provides an effective way to balance the interests of the design team members.
- The negotiation process can improve the reasoning and cross-functional understanding during design tradeoffs.
- A converged marketplace can assess the interaction and design value of different parameters even in the absence of analytical theories.
- The set-based design paradigm replaces design construction with design discovery; it allows design to proceed concurrently and defers detailed specifications until tradeoffs are more fully understood.

Table 4. Relevant Portion of Cargo Box Geometry Spreadsheet

code	NHhold	NVhold	NVdeck	B[m]	D[m]	6 40.96	8 54.48	10 69.40	12 82.92	14 97.84	16 111.36	<-# Columns <-hold length
6x4+3	6	4	3	19.6	9.96							
6x5+2	6	5	2	19.6	12.55							
6x5+3	6	5	3	19.6	12.55							
6x6+2	6	6	2	19.6	15.14							
6x6+3	6	6	3	19.6	15.14							
7x4+3	7	4	3	22.2	9.96			530	636			
7x5+2	7	5	2	22.2	12.55			510	612			
7x5+3	7	5	3	22.2	12.55		480	600				
7x6+2	7	6	2	22.2	15.14		464	580				
7x6+3	7	6	3	22.2	15.14		536	670				
8x4+3	8	4	3	24.8	9.96		480					
8x5+2	8	5	2	24.8	12.55		464					
8x5+3	8	5	3	24.8	12.55		544					
8x6+2	8	6	2	24.8	15.14		528					
8x6+3	8	6	3	24.8	15.14	456	608					

Deleted from Beam Reduction
Deleted from Depth Reduction
Deleted from further reduction (Cb concideratons, Chief Engineers requests)

- Set-based design can greatly increase the number of design alternatives considered.
- The process is robust to intermediate design errors. During the experiment, the logic used to set block coefficient was incorrect for about half of the design period. When this was discovered and corrected, the sets were still wide enough that the process was able to move forward and reach a converged solution without major rework.
- Agent effectiveness declines rapidly when they are required to participate in more than about seven markets.
- The recorded market histories permit design logic capture and institutional learning.
- The experiment utilized the qualitative set communication and reduction aspects of RAPPID, but the specific price aspects of the markets did not have an important impact. Part of this was because the design was highly constrained and part was because the process was terminated near the end of the set reduction and did not continue into the refinement phase.

The hybrid agent approach can provide a means to address the potentially limiting design communication and negotiation process in advanced cross-functional team design, even if it is virtually linked across the Internet.

Acknowledgements

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Tanya Mulholland created the web-based communications environment used in the initial experiment as a term project in NA561 Marine Product Modeling.

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REEFER CONTAINER TRANSPORT IN OPEN TOP CARGO HOLDS

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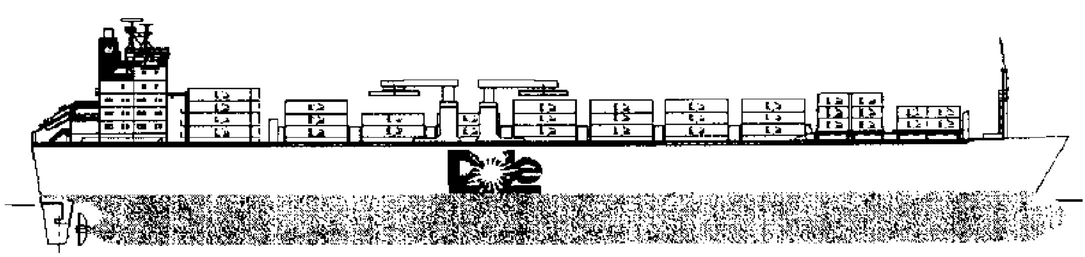
Abstract

During the last decade, increasing seaborne transportation of reefer cargo has been observed. The upwind trend of containerisation is, as for the most other cargoes, successful also with reefer cargo. Up to now, the majority of reefer containers are carried on deck. Novel reefer container ship designs stow reefer containers also in the holds. An important quantity is the entire heat generated by the reefer containers which requires a reliable layout of the ventilation system for an effective heat removal from the holds. At present, a new series of specialised container ships is under construction at Howaldtswerke Deutsche Werft AG (HDW). These ships are the largest reefer container ships in the world today with holds equipped for 100 % integral reefer containers. A major share of the reefer containers slots is planned to be equipped for modified atmosphere. HDW started an extensive research project in co-operation with Germanischer Lloyd and the consultant Dr.-Ing. Y. Wild Ingenieurbüro. The aim of the project is to study the transportation of reefer containers of different types and to derive reliable design criteria for the hold, the ventilation system of the hold, and the layout and operational behaviour of plants. Safety aspects with regard to the MA system are dealt with.

Figure 1: Newbuilding 342, Howaldtswerke Deutsche Werft AG



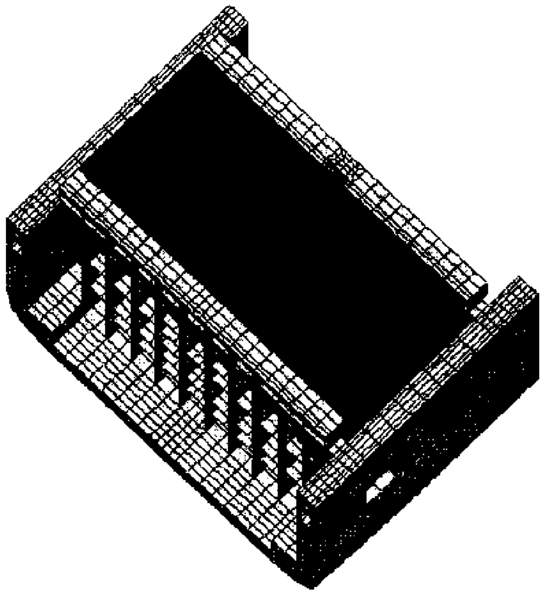
Before the detailed layout of the new series was finished, the heat generation of reefer containers with and without water cooled condensers has been measured in a laboratory set-up under different operating conditions. Temperature gauges and anemometers were used to measure the temperature and velocity field at and around the reefer container. In addition, a calculation procedure based on the finite element method was derived describing the conditions inside and outside the container. The experiments were carried out to verify and calibrate numerical and analytical investigations. At a first stage, the entire heat flow from the front side of the reefer container into the cargo hold is determined by the measurements in the test chamber and finite element calculations. Results of both measurements and finite element calculations are in good agreement, verifying the thermal performance of the reefer container and the influence of the air flow around it. Based on this results, a calculation model is set up to simulate the temperature and velocity field in the hold fully stowed with reefer containers. These numerical calculations also aim at the verification of the heat removal by air ventilation inside the hold to guarantee and optimise the geometry of the hold regarding the air flow and cooling effectiveness. The measurement results obtained in the laboratory set-up allow to specify reliable temperature and velocity boundary conditions of the global model. Finite element calculations are presented showing the entire temperature field inside the hold and demonstrate the sufficient performance of the ventilation system.

Figure 2: Refrigeration Units of Different Reefer Containers

Introduction

Two novel container vessels specially designed for the transportation of refrigerated containers are being built to Germanischer Lloyd class at Howaldtswerke-Deutsche Werft AG in Kiel for DOLE Fresh Fruit International Ltd. The capacity of some 1000 reefer containers of 40 feet corresponds to a reefer volume of about 2 million cubic feet. These ships will be the largest refrigerated ships in the world since conventional refrigerated ships have a maximum reefer capacity of about 800,000 cubic feet.

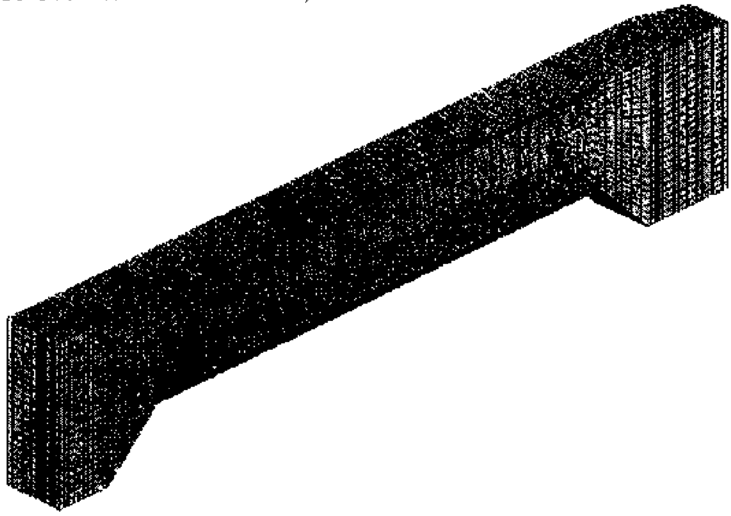
Figure 2: Arrangement of Reefer Containers, Cargo Hold 3.



The joint research and development project funded by the BMBF (German Federal Ministry of Education and Research) and entitled "Transportation of Reefer Containers in Open-Top and Conventional Cargo Holds" investigates special thermodynamic problems. The precise air flow and heat distribution relationships of a single reefer container as well as of the entire cargo hold are studied by analytical, numerical and experimental methods. The main interest in the beginning of the project was the determination of the heat dissipation by a water-cooled container refrigerating unit into the ambient air. Comprehensive measurements were performed at ATP-Meßstelle Nord GmbH in Elze, a GL subsidiary.

The test chamber in Elze, normally used to perform measurements of the over-all coefficient of heat transfer (k-coefficient) or performance tests according to ATP (Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for such Carriage) or ISO, respectively, allows the variation of the parameters air velocity, ambient and internal air temperature, humidity and heating power. All experiments were performed for the different parameters of the refrigerating unit, mains frequency (50/60 Hz) and mode of the cooling condenser (air or cooling water). A modified atmosphere was simulated for selected experiments. All thermodynamic characteristics for the deep-frozen mode and the chilled mode (bananas) could be determined under the relevant range of environmental conditions.

Figure 3: ATP Meßstelle Nord GmbH, Finite Element Model of the Test Chamber



Finite element calculations were carried out to accompany the measurements. The entire test chamber was modelled in 3D. A number of 2D and 3D sub-models were generated for comparison with selected measurements, as for example, the temperature distribution inside the container with respect to heating sources or internal fans, the heat flux through the container walls including thermal and fluid boundary layers, local models of the container front side to cover the influence of the refrigerating unit, temperature distribution at the air inlet of the chamber to investigate thermal stratification (high humidity experiments only) etc.

Novel Reefer Container Ship Design

The new container carriers are 201.5 m long, 32.2 m wide and have a draught of 10 m maximum. The power of 23,300 kW of the main propulsion plant results into a service speed of 21 knots. Two gantry cranes are available for loading and unloading of the open-top container ship. The "auxiliary" engines have a electrical output of 16,000 kW provided by three diesel-generators with 4,500 kVA and two further diesel-generators with 3,375 kVA each. The generators feed into a 6.6 kV medium voltage switchgear which supplies the major consumers, among them the transformers of the reefer container distributions and the MA compressor distributions. The switchgear is controlled by a power management system.

Thermal Performance of a Single Integral Reefer Container

General

The experiments performed at the ATP-Meßstelle Nord comprised different measurements of the heat transfer coefficient, the tightness of the integral reefer container, various operational modes, as normal and MA chilled operation (bananas), deep-freezing operation and cooling down procedures. All measurements were carried out at ambient temperatures of 20 °C and 45 °C as well as for air-cooled and water-cooled condenser mode. The test chamber is equipped with a lifting platform to allow vertical positioning of the container according to a desired distance between container walls and test chamber walls. In order to supply the tested container with cooling water, a secondary cooling circuit had to be built. An external Clip-On-Genset was used to produce a realistic power supply of the container to simulate the conditions on board (460 V / 60 Hz).

Theoretical Considerations

The accurate determination of the heat transfer between the front side of the container (hot spot) and the cargo hold is of primary importance for the design of the ventilation plant to guarantee an adequate heat removal from the hold. The amount of heat dissipated into the cargo hold differs significantly for the two operational modes of the condenser. In case of air-cooling, nearly all the heat is transferred from the condenser to the hold at the front side of the container. In the case of water cooling, the majority of the heat is transferred to the cooling agent, and only a minor part is transferred to the air in front of the container via the condenser and compressor surfaces. Different heat flows were specified and measured to allow the calculation of heat balance equations for the different experimental set-ups. These heat flows comprise

1. entire heat flow from container front side to cargo hold incl. conduction, radiation etc.
2. conduction through the container walls (front side excluded),
3. heat flow of the cooling water (in/out),
4. electrical heating inside the container (simulation of the ripening process),
5. power input (gen-set),
6. heat flow of the air exchanged between the container and the test chamber generated by the refrigerating unit (in/out) and
7. heat flow of the air at the inlet/outlet of the test chamber.

Since the sum of all heat flows is zero in the balance equation, the unknown part of the front side (no.1) can easily be determined.

Figure 4: Heat flow balance for the cargo hold and the container

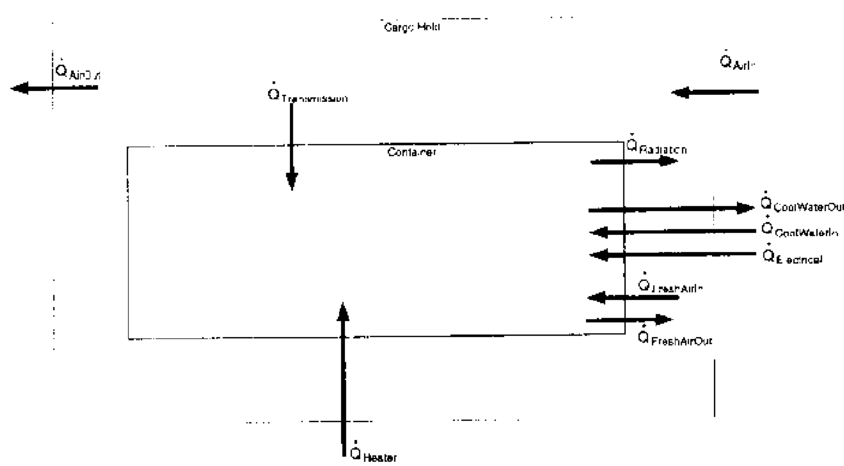
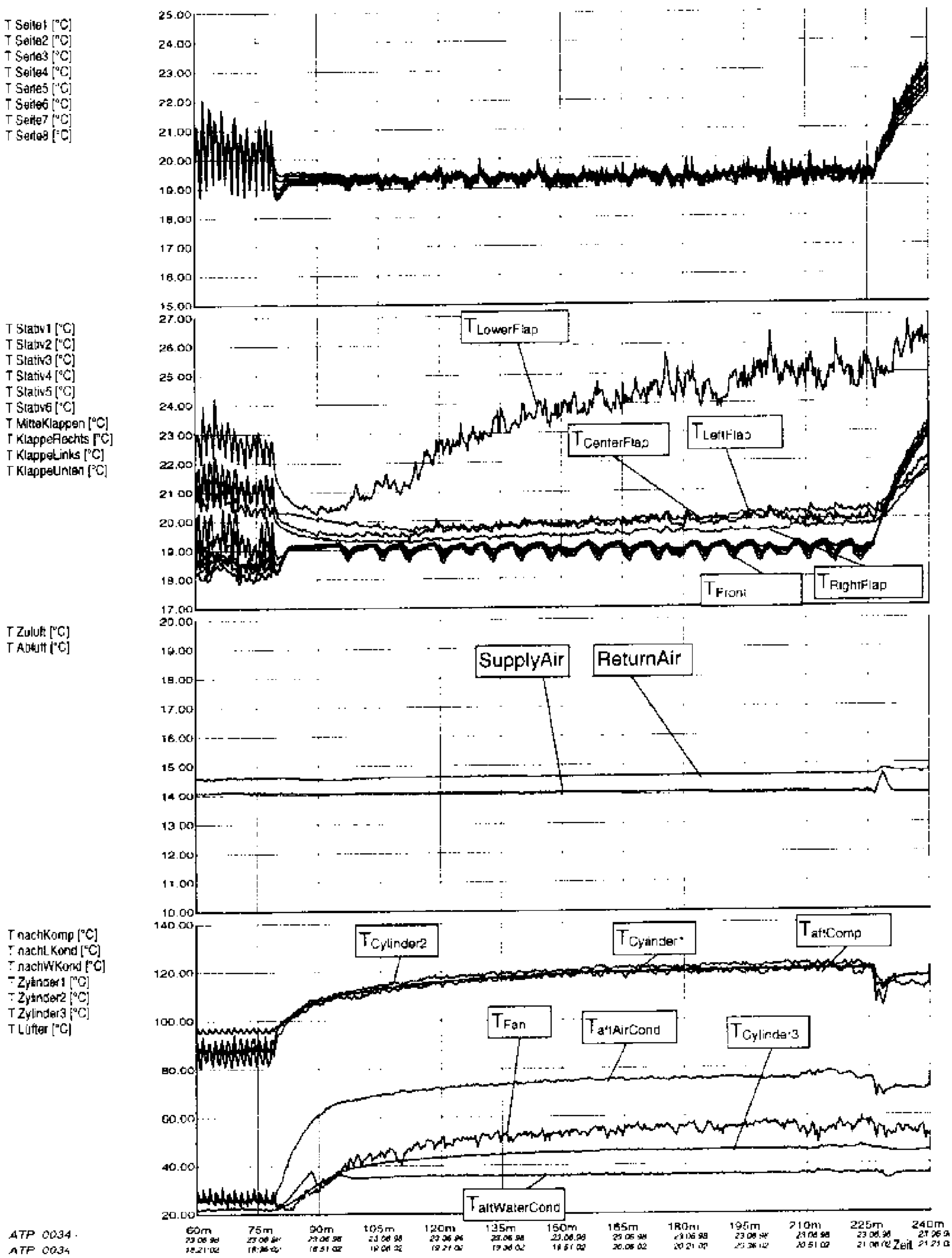


Figure 5: Transient temperature development of selected parts of the refrigerating unit for normal chilled operation



Measurement Results

The results of the measurements gave a clear picture of the thermodynamic characteristics. A heat transfer coefficient of k=0,34 W/m^{2}K was measured according to ATP. A modified experimental setup including air ventilation inside the container, as is the case for refrigerating operation, resulted in a correspondingly higher value of k=0,4146 W/m^{2}K. The latter value was used for the calculation of the heat flow through the container walls.

Numerical considerations

A time-averaged Navier-Stokes solver with a modified k-ε turbulence model was applied. The general purpose CFD-code ANSYS based on a finite element formulation was used to solve all cases. Various calculations were carried out for verification and calibration purposes.

The temperature gradient ∇T can easily be determined by the calculated temperature distribution in the boundary layer inside and outside the container. The respective heat flow q is then obtained by multiplication of ∇T with the thermal conductivity λ. The temperature dependence of λ must be observed due to the significant temperature difference ΔT between inner container and outer test chamber. The surface coefficient of heat transfer α is given by

$$\alpha_{in} = \frac{\dot{q}_{int}}{\Delta T} = \frac{\lambda(T_{int}) \cdot \nabla T_{int}}{\Delta T} \quad \text{and} \quad \alpha_{out} = \frac{\dot{q}_{out}}{\Delta T} = \frac{\lambda(T_{out}) \cdot \nabla T_{out}}{\Delta T}$$

With t as the wall thickness of the container, the heat transfer coeficient k reads

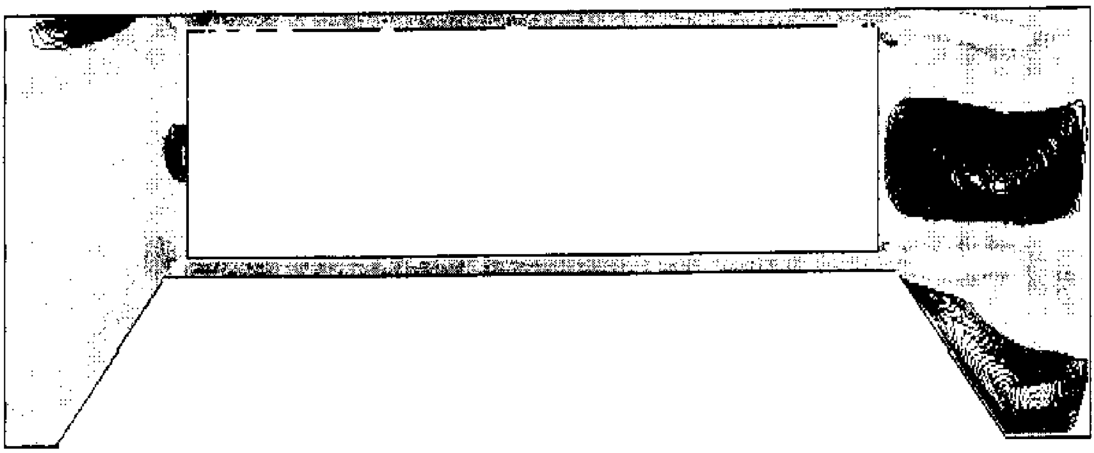
$$k = \left(\frac{1}{\alpha_{in}} + \frac{t_{container}}{\lambda_{container}} + \frac{1}{\alpha_{out}} \right)^{-1}$$

This value can directly be compared with the measured heat transfer coefficient.

Numerical results

Figure 6 shows a 2D cross-section (side-view) through the 40-feet container which is located in the middle of the test chamber on a lifting platform. The distance to the bottom/ceiling is approx. 0.3 m and a significant increase of the air speed is observed. Four anemometers were installed between container wall and test chamber wall to determine the (mean) velocity around the container. The velocity at the inlet was measured manually by using a hand-held anemometer. A vertical arrangement of temperature sensors was installed at the inlet to check the vertical temperature profile. Both inlet velocity and inlet temperatures are specified as boundary conditions. At the outlet the pressure is set to p=0. At the container front side, either the measured temperature distribution of the refrigerating unit or the heat generation can be specified. All (other) walls are non-slip walls.

Figure 6: Velocity distribution around the 40-feet container at ATP-Meßstelle Nord in Elze



The air entrance to the chamber is at the left hand side where also the front side of the container is located. The air cooled operation mode can be deduced from the (minimum) velocity of the ventilator of the refrigerating unit arranged directly above the condenser. At the right hand side a recirculation area above the chamber outlet is observed and verified by the calculations. It has only a minor influence on the temperature distribution which is nearly homogenious at the outlet. Significant temperature gradients are observed only at and around the front side of the container (hot spot).

Figure 7 shows a 2D cross-section (top-view) through the 40-feet container and the test chamber. Only one half of the model is generated for symmetry reasons, and only the outlet of the chamber including approx. 20 % of the rear side of the container is displayed. The temperature (left hand side) inside the container is nearly constant, whereas a strong temperature gradient is calculated close to and through the wall. A small influence of the velocity distribution (right hand side) on the temperature is observed outside the container where the distance to the chamber wall is close. A small energy transport at the rear side of the container close to the wall can be seen in figure 7 by a slightly increased temperature field.

Cargo Hold Ventilation

Gerneral

The novel container ships carry 884 reeefer containers in the hold, of which 789 units are in open spaces and 95 in closed rooms. The large amount of heat dissipated from the containers can not be removed by conventional refrigerating units equipped with air-cooled condensers. All units used for this ship are therefore fitted with both air-cooled and water-cooled condensers and are hooked up to the freshwater cooling system by quick couplings.

Figure 7: Temperaure distribution around the 40-feet container at ATP-Meßstelle in Elze

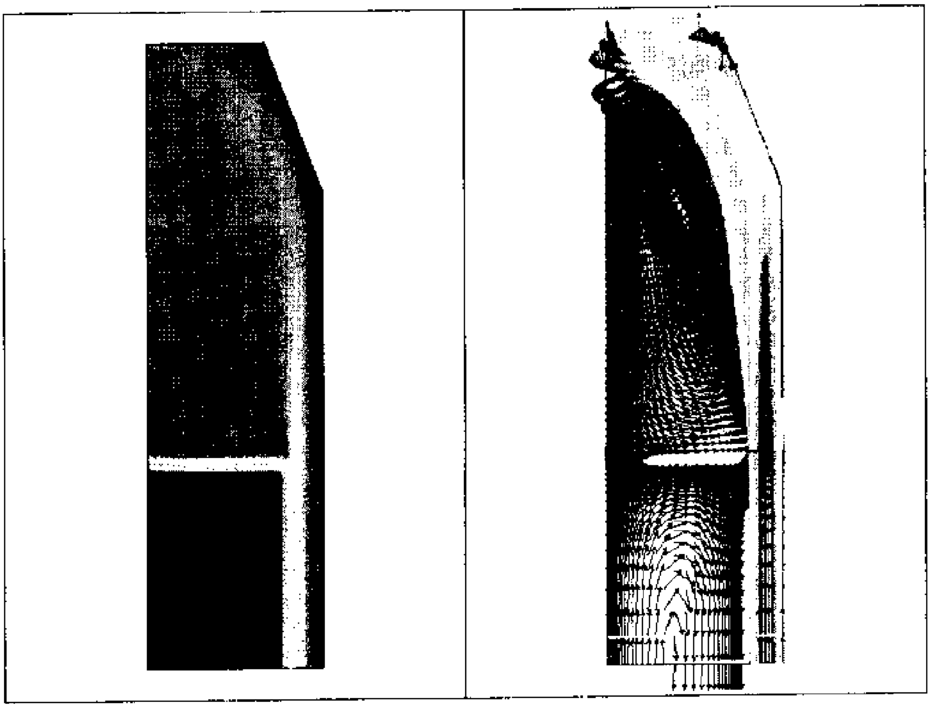
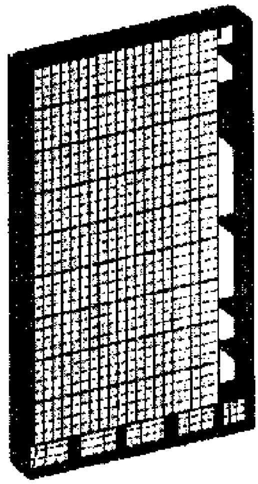


Figure 8 shows the arrangement of the containers inside the cargo holds in longitudinal direction. For calculation of the temperature distribution in the hold only the space in front of the containers is taken into consideration as in this space the major air circulation is taking place.

Since the entire heat to be removed from the cargo hold is measured and verified, suitable assumptions on the cargo hold ventilation can be made in order to specify velocity and temperature boundary conditions at the positions of the fans.

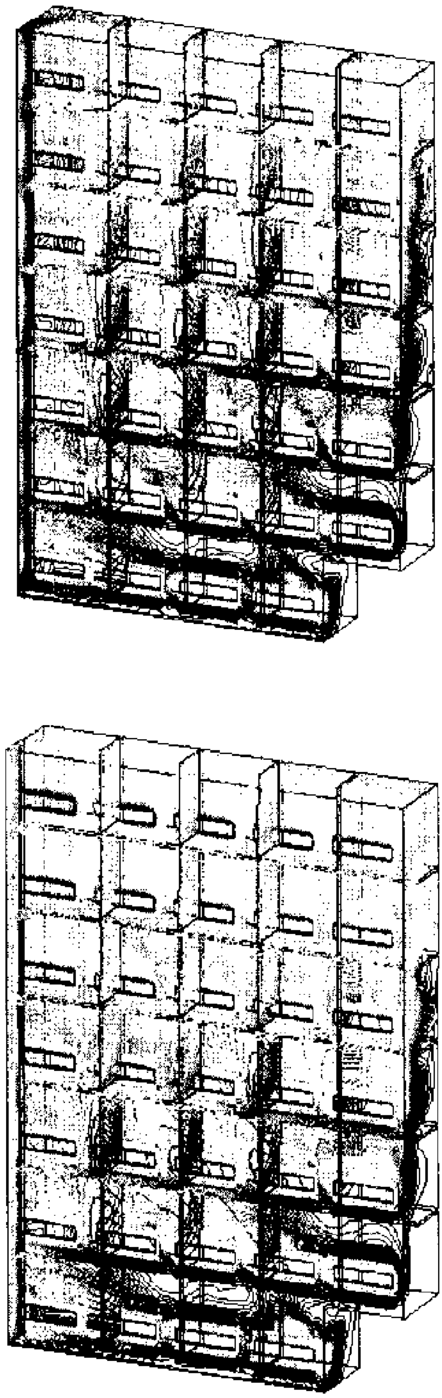
Figure 8: Arrangement of the containers inside the cargo hold



Taking into account the temperature difference between the cooling air and the container front side, the entire cooling air quantity can be calculated via the density and specific heat. As in the case of the ATP-Meßstelle, the thermodynamic behaviour of the refrigerating unit can either be modelled by a certain temperature distribution on the frotnt surface of the container or by a prescibed heat generation. If a heat generation is set according to the measured values, the resulting temperature distribution also have to correspond to the measurements. If the temperatures are specified at the container front side, as it is the case in figure 9, the integration of the resulting heat flux distribution must be in agreement with the measured heat dissipation.

The hold companionways are modelled in detail to guarantee an accurate calculation of the energy transport by the air flow in upward direction. The curved isotherms on the right hand side of figure 9 indicate that the streamlines of the convectional fluid are influenced by the companionways. The gratings have an influence on the fluid. A suitable method to cover the resistance of the gratings is to introduce a "distributed resistance" model which allows the prescription of an adjustable change in the dynamic pressure along a line (2D) or area (3D). To adjust the coefficients of the distributed resistance model, a separate finite element model was generated similar to figure 9 comprising three companionways in horizontal direction. The gratings were modelled in detail and the pressure distribution was investigated for different combinations of temperature and velocity boundary conditions. The influence of the gratings obtained by the distributed resistance model was calibrated by the results of the detailed model. Finally, only a small number of elements is necessary to include the gratings into the 3D model of the entire cargo hold. The distance between gratings and container front side is also a parameter investigated within the project. A minimum distance is desired for costs reasons. On the other hand, the entire heat dissipated from the containers has to removed from the cargo hold. An additional safety margin can easily be calculated for higher cooling temperatures, failure of the ventilation system etc.

Figure 9: Temperature distribution inside the cargo hold for ambient temperatures of 20°C (top) and 45 °C (bottom)



Controlled Atmosphere

A number of reefer containers are operated with a modified atmosphere (MA). The reefer cargo is exposed to a nitrogen-enriched environment which significantly reduces the metabolism of the fruit and vegetables. The effects of MA or CA (controlled atmosphere) on the refrigerated goods depend on the product and type. In the case of bananas, the ripening process can be retarded considerably. The advantages of this method are, among others, a transportation of the bananas in a riper state yielding a better taste, reduction of the chemical post-harvest treatment, extension of the transport period, reduction of transport losses etc.

The nitrogen generation plant is currently designed for supplying the reefer containers intended for holds 3 and 4. The plant is separated off from the engine room and has already been prepared for future extension. The design capacity of the nitrogen generation plant is currently 1,000 Nm^3/h with an N_2 purity of 95 %. The nitrogen is obtained by the membrane method. The membrane unit is made of parallel arranged hollow-fibre membranes. The faster oxygen molecules move through the membrane walls to the outside and are bled off to the atmosphere at a safe point. The slower nitrogen portion remains inside the membrane walls and is passed to the reefer containers via a piping system. A residual oxygen content of approx. 3-4 % inside the continuously flushed reefer containers is desired. The plant and all essentiell components were examined and certified at the manufacturer´s works by Germanischer Lloyd.

As a part of the research and development project, safety aspects with regard to MA or CA are also being examined. Of particular interest are the factors that must be considered for oxygen-reduced or -enriched atmospheres to identify hazardous areas. Areas as cargo holds, MA machinery space and pipe ducts etc. have been identified as dangerous areas with respect to oxygen depletion. The minimum forced air ventilation has been determined. In case of a shut-off of cargo hold ventilation the oxygen content may drop below a safe level of approx. 10 % by volume. Correspondingly, oxygen monitoring and alarm systems are necessary to be installed to ensure a safe entrance into these areas during maintenance and repair works, loading and unloading processes etc. Finally, an acoustic and visual alarm is to be installed within and at the entrance of each hazardeous area.

Further Research Work

During 1999 a measurement voyage on an older reefer container vessel will be undertaken to verify the results of the finite element analysis for the case of a closed cargo hold. The velocity and temperature distribution inside the cargo hold will be measured at normal chilled operation with bananas at different ambient temperatures.

After completion of HDW newbuilding 342, a second measurement voyage will be undertaken and the corresponding finite element calculations for open holds will be compared with values obtained from shipboard measurements.

Conclusion

The transportation of refrigerating cargo in open top container ships is a novel trend. The newbuildings 342 and 343 built to Germanischer Lloyd class at Howaldtswerke-Deutsche Werft AG in Kiel for DOLE Fresh Fruit International Ltd HDW have a reefer volume of 2 million cubic feet making them the largest reefer container ships worldwide. Since the majority of the water-cooled integral reefer containers are carried in the holds, special attention must be paid to the layout of the ventilation system for an effective heat removal from the holds.

The heat generation of a reefer containers has been measured in a laboratory set-up under all relevant operation conditions. The experiments were carried out to verify and calibrate finite element calculations and analytical investigations. The results of both measurements and finite element calculations of a single container are extrapolated to the thermodynamics of the entire cargo hold and allowed the specification of the cargo ventilation design at an very early stage. Finite element calculations of the air ventilation inside the cargo hold will be compared with experimental values for conventional and open-top cargo holds.

Owing to the fact that controlled or modified atmosphere systems are more and more applied onboard reefer container ships, Germanischer Lloyd will extend it's regulations which are presently applicable to traditional reefer ships to reefer container ships of novel design.

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ESTIMATING RESISTANCE AND PROPULSION FOR SINGLE-SCREW AND TWIN-SCREW SHIPS IN THE PRELIMINARY DESIGN

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Introduction

One of the essential problems in the preliminary design phase of a newbuilding project is the prognosis of resistance and propulsion. This prognosis has an indirect influence on both the delivery date and the quoted price of a project. In the case of a project for which no satisfactory price can be secured and which is to be realized within a limited period of time, the design engineer will have to allow for increased reserves regarding speed and/or efficiency. In such a case neither the money nor the time available will be sufficient to enable expensive optimization of the hull form. On the other hand, if a satisfactory price can be obtained for a project and if adequate lead time is given for production, both time and financial resources available will be such as to permit expensive optimization and efficiency prognosis at the bottom end of the scale.

Nearly all known methods for estimating hull resistance are suitable for single-screw ships only. Moreover, most of the methods are inappropriate for estimating the resistance of short, beamy vessels and of vessels with large block coefficients. Therefore, in the absence of relevant reference vessels, prognoses for single-screw ships of short lengths and large breadths or with large block coefficient and for twin-screw ships in general imply major uncertainties.

Also, the question as to whether the predicted speed can already be considered as the optimum speed or whether it will still be possible for improvements to be achieved cannot be answered by means of the traditional methods for estimating hull resistance. It is equally difficult to estimate a resistance which will even under unfavorable boundary conditions of the design almost certainly not be exceeded.

The present paper contributes to assessing the problems referred to above in the early design phase, in which little detail information is as yet available, with greater reliability than has been possible so far.

Comparison of Traditional Methods with Modern Resistance Data

Traditional methods to estimate resistance in conceptual ship design follow e.g. Holtrop-Mennen *(Holtrop 1984)*, *Guldhammer-Harvald (1974)*, *Danckwardt (1985)*, Lap-Keller *(Lap 1954, Keller 1973)*, Series 60 *(Sabit 1972)*, *Danckwardt (1981)* (for trawlers) and *Oortmerssen (1971)*. However, all these methods are based on ship forms which may be considered obsolete, and there has been growing concern regarding the applicability of these methods to modern ship hulls. Therefore, the database of the Vienna Ship Model Basin for the years 1980 to 1995 is used to evaluate the accuracy of these traditional methods. The database covered 433 models (1218 variants) with protocols of 793 resistance tests and 1103 propulsion tests each for a set of different speeds.

The traditional estimation methods proved to be quite reliable in predicting the resistance of an average-single screw ship, **Table 1**. They are unsuitable for twin-screw ships except for the methods of Holtrop-Mennen and, to some extent, Guldhammer-Harvald. Lap-Keller and Series 60 methods are only suitable for single-screw ships on design draft. Oortmerssen and Danckwardt for Trawler methods are at best suited for small ships, but they show higher standard deviations than other methods.

Table 1. Average and Standard Deviation of (Model Test Resistance – Estimated Resistance)

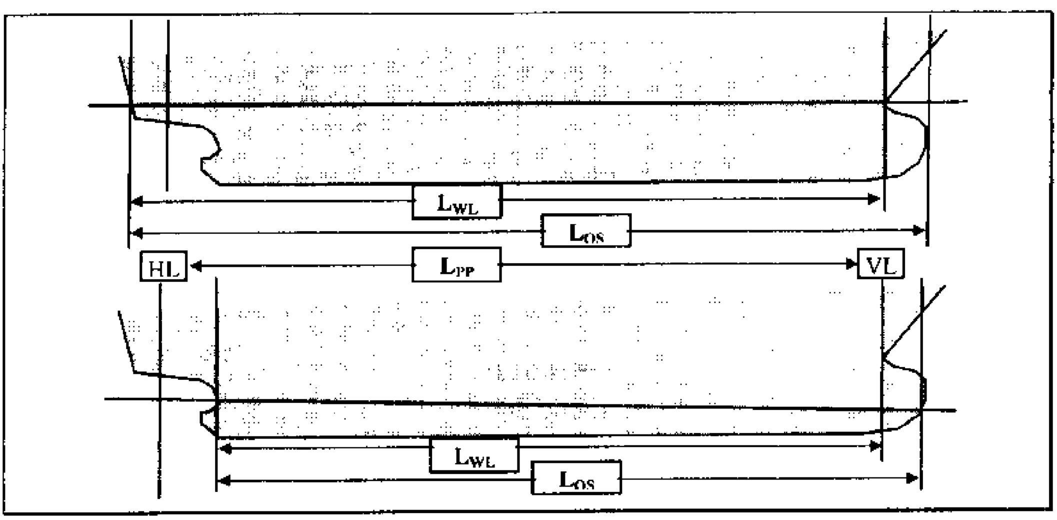
Method	Single-Screw Ships			Twin-Screw Ships		
	out of range	average deviation	standard deviation	out of range	average deviation	standard deviation
Holtrop-Mennen	6.6 %	+2.7 %	13.4 %	8.9 %	+8.4 %	17.9 %
Guldhammer-Harvald	17.5 %	+4.8 %	15.2 %	39.9 %	+12.1 %	23.0 %
Danckwardt 87	7.6 %	+4.1 %	14.8 %	94.7 %	+26.0 %	34.4 %
Lap-Keller	56.1 %	+2.9 %	13.4 %	95.3 %	+16.2 %	19.7 %
Series 60	62.0 %	+2.4 %	13.4 %	96.9 %	+17.7 %	22.4 %
Van Oortmerssen	97.4 %	+5.7 %	14.8 %	88.1 %	+6.8 %	20.2 %
Danckwardt Trawler	91.7 %	-4.3 %	17.9 %	96.6 %	+17.9 %	31.5 %

The results of the traditional methods will in the following be called "mean resistance". The comparison of traditional methods with modern data led to the conclusion that it is useful to have also formulae for the lower and the upper envelope curves of the statistical data which are exceeded by only 5% of the cases. These lower and upper envelope curves of the statistical data are called here "minimum" and "maximum" resistance. The "minimum" resistance is taken as an estimate of what may be achieved by excellent lines not subject to severe constraints from the design and found after extensive further computer and model test investigations. The "maximum" may represent lines subject to unusual constraints from the overall design. These envelopes are not part of the classical prediction methods.

New Estimation Method for Resistance

Variables not explicitly specified have a meaning according to ITTC standard. All lengths are taken in [m]. In addition to lengths L_{PP} and L_{WL}, which are defined as usual, a "Length over surface" L_{OS} is defined as follows, **Fig. 1**:

Fig. 1 Definition of Lengths L_{PP}, L_{WL} and L_{OS}



The "**Length over surface**" L_{OS} is defined as follows:

- For design draft: length between aft end of design waterline and most forward point of ship below design waterline.
- For ballast draft: length between aft end and forward end of ballast waterline (rudder not taken into account).

The Froude number in the following formulae is based on the length L_{Fn}:

$$
\begin{aligned}
L_{Fn} &= L_{OS} && \text{for } L_{OS} < L_{PP}, \text{ else ...} \\
L_{Fn} &= L_{PP} + 2/3 \cdot (L_{OS} - L_{PP}) && \text{for } L_{OS} < 1.10\, L_{PP}, \text{ else ...} \\
L_{Fn} &= 1.0667 \cdot L_{PP} && \text{for } L_{OS} \geq 1.10\, L_{PP}
\end{aligned} \tag{1}
$$

Wetted Surface of Hull and Appendages

For estimation of the frictional resistance the wetted surface of hull and appendages has to be known. In case that no exact data are available, the following formula can be used for estimating the wetted surface of hull and appendages for single-screw and twin-screw vessels:

$$S_{Total} = k \cdot L_{PP} \cdot (B + 2 \cdot T) \tag{2}$$

with

$$
\begin{aligned}
k = {} & a_0 + a_1 \cdot (L_{OS}/L_{WL}) + a_2 \cdot (L_{WL}/L_{PP}) + a_3 \cdot (C_B) + a_4 \cdot (L_{PP}/B) \\
& + a_5 \cdot (B/T) + a_6 \cdot (L_{PP}/T) + a_7 \cdot ((T_A - T_F)/L_{PP}) + a_8 \cdot (D_P/T) \\
& + k_{Rudder} \cdot (N_{Rudder}) + k_{Brackets} \cdot (N_{Brackets}) + k_{Bossings} \cdot (N_{Bossings})
\end{aligned} \tag{3}
$$

The following coefficients have been determined, **Table 2**:

Table 2. Coefficients for Estimating the Wetted Surface

	Single Screw Vessel		**Twin Screw Vessel**	
	with and without bulbous bow		with bulb	without bulb
	design draft	ballast draft	design draft	design draft
a_0	-0.6837	-0.8037	-0.4319	-0.0887
a_1	0.2771	0.2726	0.1685	0
a_2	0.6542	0.7133	0.5637	0.5192
a_3	0.6422	0.6699	0.5891	0.5839
a_4	0.0075	0.0243	0.0033	-0.0130
a_5	0.0275	0.0265	0.0134	0.0050
a_6	-0.0045	-0.0061	-0.0005	-0.0007
a_7	-0.4798	0.2349	-2.7932	-0.9486
a_8	0.0376	0.0131	0.0072	0.0506
k_{Rudder}	---	---	0.0131	0.0076
$k_{Brackets}$	---	---	-0.0030	-0.0036
$k_{Bossings}$	---	---	0.0061	0.0049

For single-screw vessels the area of the rudder is already included in the formula. For twin-screw vessels it has to be observed that the number of rudders has to be either one or two. There have to be either two brackets, or two bossings. With the formula it is not possible to calculate the hull surface of a twin-screw vessel without any appendage.

The standard deviation, when using these coefficients results in 2.3% for single-screw vessels at design draft, 4.0% for single-screw vessels at ballast draft, 3.6% for twin-screw vessels with bulbous bow and 4.6% for twin-screw vessels without bulbous bow.

Residual Resistance

The resistance is decomposed without using a form factor. Note that 0.10 • (B • T) is used instead of the wetted surface S as reference area. The residual resistance is given by:

$$R_R = C_R \cdot (\rho/2 \cdot V^2 \cdot 0.10 \cdot (B \cdot T)) \tag{4}$$

Note that 0.10 • (B • T) is used instead of the wetted surface S as reference area. The following formulae can be used to estimate the non-dimensional residual resistance coefficient C_R for "mean" and "minimum" values as:

$$\begin{aligned} C_R = {} & C_{R\,(Std)} \cdot C_{R\,(Fn)} \cdot k_{Lpp} \cdot (T/B)^{a1} \cdot (B/L_{PP})^{a2} \cdot (L_{OS}/L_{WL})^{a3} \cdot (L_{WL}/L_{PP})^{a4} \\ & \cdot (1+(T_A-T_F)/L_{PP})^{a5} \cdot (D_P/T_A)^{a6} \cdot N_{Rudder}{}^{a7} \cdot N_{Brackets}{}^{a8} \cdot N_{Bossings}{}^{a9} \\ & \cdot N_{Thrusters}{}^{a10} \end{aligned} \tag{5}$$

T_A is the draft at aft perpendicular, T_F the draft at forward perpendicular, D_P is the propeller diameter, N_{Rudder} the number of rudders [1 or 2], $N_{Brackets}$ the number of brackets [0...2], $N_{Bossings}$ the number of bossings [0...2] and $N_{Thrusters}$ is the number of side thrusters [0...4].

For the standard residual resistance coefficient $C_{R\,(std)}$:

$$\begin{aligned} C_{R\,(Std)} = {} & b_{11} + b_{12}\,F_n + b_{13}\,F_n^2 + C_B \cdot (\,b_{21} + b_{22}\,F_n + b_{23}\,F_n^2) \\ & + C_B^2 \cdot (\,b_{31} + b_{32}\,F_n + b_{33}\,F_n^2) \end{aligned} \tag{6}$$

To take into account the increasing residual resistance above critical Froude number:

$$C_{R\,(Fn)} = \text{maximum of } [\,1.0 \text{ and } (F_n / F_{n\,(crit.)})^{c1}\,] \tag{7}$$

$$F_{n\,(crit.)} = d_1 + d_2\,C_B + d_3\,C_B^2 \tag{8}$$

To take into account the residual resistance depending on the vessels length:

$$k_L = e_1 \cdot L_{pp}\,[m]^{e2} \tag{9}$$

The formulae and coefficients are valid in the following range of Froude numbers

$$F_{n\,(min)} = \text{minimum of } [\,f_1 \text{ and } f_1 + f_2\ (f_3 - C_B)\,)\,] \tag{10}$$

$$F_{n\,(max)} = g_1 + g_2\,C_B + g_3\,C_B^2 \tag{11}$$

The "maximum" total resistance is:

$$R_{T\,(max)} = h_1 \cdot R_{T\,(mean)} \tag{12}$$

Note the valid range of main dimensions and main dimension ratios when using the above formulae. **Table 3** gives the relevant coefficients for calculating the residual resistance.

Table 3. Coefficients for Calculating the Residual Resistance

	"Mean" Resistance			"Minimum" Resistance	
	single-screw		twin-screw	single-screw	twin-screw
	design draft	ballast draft	design draft	design draft	design draft
a_1	-0.3382	-0.7139	-0.2748	-0.3382	-0.2748
a_2	0.8086	0.2558	0.5747	0.8086	0.5747
a_3	-6.0258	-1.1606	-6.761	-6.0258	-6.761
a_4	-3.5632	0.4534	-4.3834	-3.5632	-4.3834
a_5	9.4405	11.222	8.8158	0	0
a_6	0.0146	0.4524	-0.1418	0	0
a_7	0	0	-0.1258	0	0
a_8	0	0	0.0481	0	0
a_9	0	0	0.1699	0	0
a_{10}	0	0	0.0728	0	0
b_{11}	-0.57424	-1.50162	-5.3475	-0.91424	3.27279
b_{12}	13.3893	12.9678	55.6532	13.3893	-44.1138
b_{13}	90.596	-36.7985	-114.905	90.596	171.692
b_{21}	4.6614	5.55536	19.2714	4.6614	-11.5012
b_{22}	-39.721	-45.8815	-192.388	-39.721	166.559
b_{23}	-351.483	121.82	388.333	-351.483	-644.456
b_{31}	-1.14215	-4.33571	-14.3571	-1.14215	12.4626
b_{32}	-12.3296	36.0782	142.738	-12.3296	-179.505
b_{33}	459.254	-85.3741	-254.762	459.254	680.921
c_1	$F_n / F_{n\,(crit)}$	$10\,C_B\,(F_n / F_{n\,(crit)}-1)$	$F_n / F_{n\,(crit)}$	0	0
d_1	0.854	0.032	0.897	0	0
d_2	-1.228	0.803	-1.457	0	0
d_3	0.497	-0.739	0.767	0	0
e_1	2.1701	1.9994	1.8319	0	0
e_2	-0.1602	-0.1446	-0.1237	0	0
f_1	0.17	0.15	0.16	0.17	0.15
f_2	0.2	0.1	0.24	0.2	0
f_3	0.6	0.5	0.6	0.6	0
g_1	0.642	0.42	0.83	0.614	0.952
g_2	-0.635	-0.2	-0,66	-0.717	-1.406
g_3	0.15	0	0	0.261	0.643
h_1	1.204	1.194	1.206		

L_{PP} [m]	42.0 ... 205.0	50.2 ... 224.8	30.5 ... 206.8	42.0 ... 205.0	30.5 ... 206.8
$L_{PP}/\nabla^{(1/3)}$	4.49 ... 6.01	5.45 ... 7.05	4.41 ... 7.27	4.49 ... 6.01	4.41 ... 7.27
C_B	0.60 ... 0.83	0.56 ... 0.79	0.51 ... 0.78	0.60 ... 0.83	0.51 ... 0.78
L_{PP}/B	4.71 ... 7.11	4.95 ... 6.62	3.96 ... 7.13	4.71 ... 7.11	3.96 ... 7.13
B/T	1.99 ... 4.00	2.97 ... 6.12	2.31 ... 6.11	1.99 ... 4.00	2.31 ... 6.11
L_{OS}/L_{WL}	1.00 ... 1.05	1.00 ... 1.05	1.00 ... 1.05	1.00 ... 1.05	1.00 ... 1.05
L_{WL}/L_{PP}	1.00 ... 1.06	0.95 ... 1.00	1.00 ... 1.07	1.00 ... 1.06	1.00 ... 1.07
D_P/T_A	0.43 ... 0.84	0.66 ... 1.05	0.50 ... 0.86	0.43 ... 0.84	0.50 ... 0.86

Test Computations compared with the Fundamental Database

Test computations with the new method compared with the fundamental database of the Vienna Ship Model Basin were evaluated twice: at first taking into account and secondly without taking into account the limiting values of main dimensions and main dimension ratios for each type of vessel (e.g. all results available have been compared). A positive average deviation means that the model test resistance was higher than the estimated resistance.

Without taking account the limiting values of main dimensions, but taking into account the limits for Froude number, the following average and standard deviations occurred, **Table 4**:

Table 4. Average and Standard Deviations, without taking into Account the Limiting Values

Type of Vessel	Bulb. Bow	Condition	No of Tests		Min.	Max.	Average	Stand.
			N_{Total}	$N_{Hollenb}$	%	%	%	%
single-screw	no	ballast	19	19	-12.3	+22.2	-0.49	10.7
single-screw	no	design	79	79	-29.7	+30.6	-1.11	12.6
single-screw	no	total	98	98			-0.99	12.2
single-screw	yes	ballast	73	73	-25.3	+25.2	-0.80	10.9
single-screw	yes	design	277	277	-27.7	+26.5	+0.92	10.1
single-screw	yes	total	350	350			+0.56	10.3
single-screw	total	total	448	448			+0.22	10.7
twin-screw	no	design	60	60	-57.6	+44.2	-6.46	23.0
twin-screw	yes	design	163	163	-39.5	+30.1	+0.77	12.4
twin-screw	total	design	223	223			-1.18	15.3
total			671	671	-57.6	+44.2	-0.25	12.2

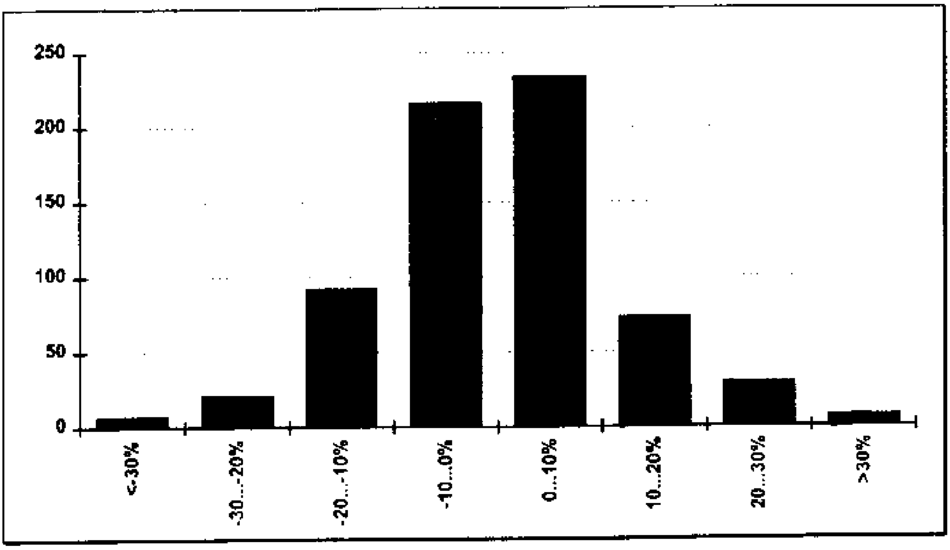
496 resistance tests (73.9%) of 671 resistance tests in total are within the limiting values of the new method, 175 resistance tests are out of range, **Table 5**.

Table 5. Average and Standard Deviation taking into Account the Limiting Values

Type of Vessel	Bulb. Bow	Condition	No of Tests		Min.	Max.	Average	Stand.
			N_{Total}	$N_{Hollenb}$	%	%	%	%
single-screw	no	ballast	19	9	-9.7	+7.3	-2.43	8.6
single-screw	no	design	79	59	-23.5	+30.6	+0.48	10.5
single-screw	no	total	98	68			+0.09	10.2
single-screw	yes	ballast	73	52	-18.3	+19.1	-2.06	9.9
single-screw	yes	design	277	212	-27.7	+26.5	+1.63	9.5
single-screw	yes	total	350	264			+0.72	9.6
single-screw	total	total	448	332			+0.59	9.7
twin-screw	no	design	60	24	-31.4	+13.2	-6.87	9.4
twin-screw	yes	design	163	140	-27.8	+24.3	+0.13	10.4
twin-screw	total	design	223	164			-0.89	10.3
total			671	496	-31.4	+30.6	+0.10	9.9
out of range				175			+3.43	16.2

Where L_{OS}/L_{WL}, L_{WL}/L_{PP} and D_P/T_A have been out of range during test computations, not the original value of the model itself has been used, but the corresponding limiting value instead. The distribution of average deviation of the new method from the results of the resistance tests, taking into account the above-mentioned limiting values, is shown in **Fig. 2**:

Fig. 2 Distribution of Average Deviation of (Model Test Resistance – Estimated Resistance)



The new method predicts much better not only the resistance of twin screw vessels, but also the resistance of single-screw vessels with large block coefficient (C_B > 0.78) and with small length/breadth ratios (L_{PP}/B < 5.5), **Table 6**:

Table 6. Average and Standard Deviation for large C_B and small L_{PP}/B Ratios

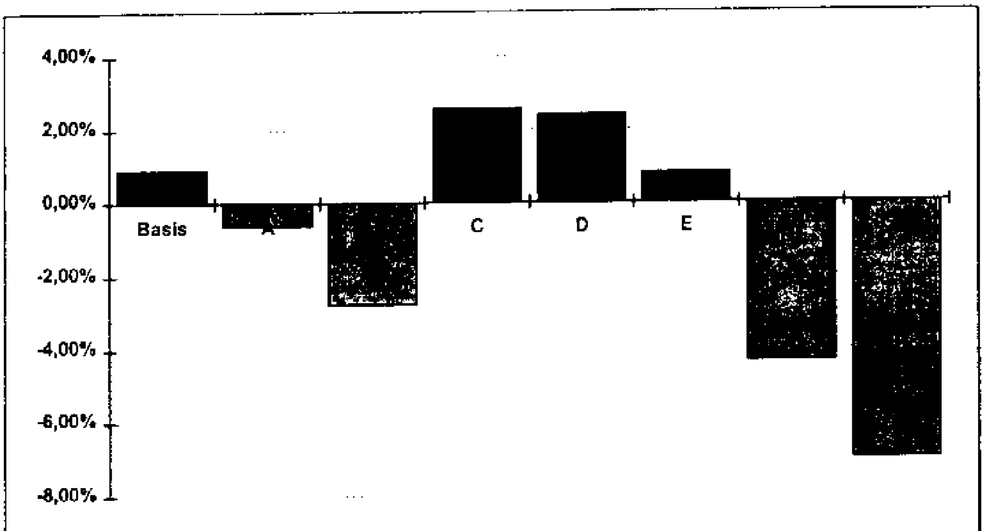
Method	C_B > 0.78			L_{PP}/B < 5.5		
	out of range	average deviation	standard deviation	out of range	average deviation	standard deviation
Holtrop-Mennen	20.0 %	+3.1 %	13.2 %	61.0 %	+12.9 %	19.7 %
Guldhammer-Harvald	72.2 %	+4.5 %	14.5 %	52.5 %	+12.3 %	17.7 %
Danckwardt 87	25.2 %	–3.2 %	13.4 %	50.0 %	+8.7 %	15.8 %
Lap-Keller	86.1 %	–3.0 %	9.5 %	74.6 %	+8.3 %	16.5 %
Series 60	81.7 %	–2.1 %	12.5 %	99.2 %	–21.3 %	21.3 %
Hollenbach, no limits	0 %	+0.4 %	11.4 %	0 %	–0.6 %	13.2 %
Hollenbach, with limits	29.8 %	+1.4 %	10.4 %	38.6 %	+2.0 %	12.0 %

Improvements depending on the Number of Modifications

The database includes resistance tests with the initial form and, if modifications have been investigated, the final form of each vessel. Intermediate stages of modifications are not included in the database. In total 275 resistance tests of initial forms and 228 resistance tests of final forms are available. Determining the average deviation dependent on the number of modifications may give an indication of the effort which will be necessary to achieve a certain improvement in the resistance characteristic for a newbuilding project.

Initial forms on an average have a slightly higher resistance than predicted by the new method, the average deviation is +0.9%. Models which have been modified once (68 models, version A) have an average deviation of –0.6%, models which have been modified twice (42 models, version B) have an average deviation of –2,8%. Models, which have been modified more than twice and less than six times, have had insufficient resistance characteristics in the initial form and still have resistance characteristics in the final form which are below average (42 models - version C, 23 models - version D, 18 models - version E). Only models, which have been modified six times and more (13 models - version F and 22 models - versions G to T), are significantly better than average (–4,3% to –7,0%).

Fig. 3 Deviation from "Mean Resistance" dependent on Number of Modifications



Average Deviation depending on the Type of Vessel

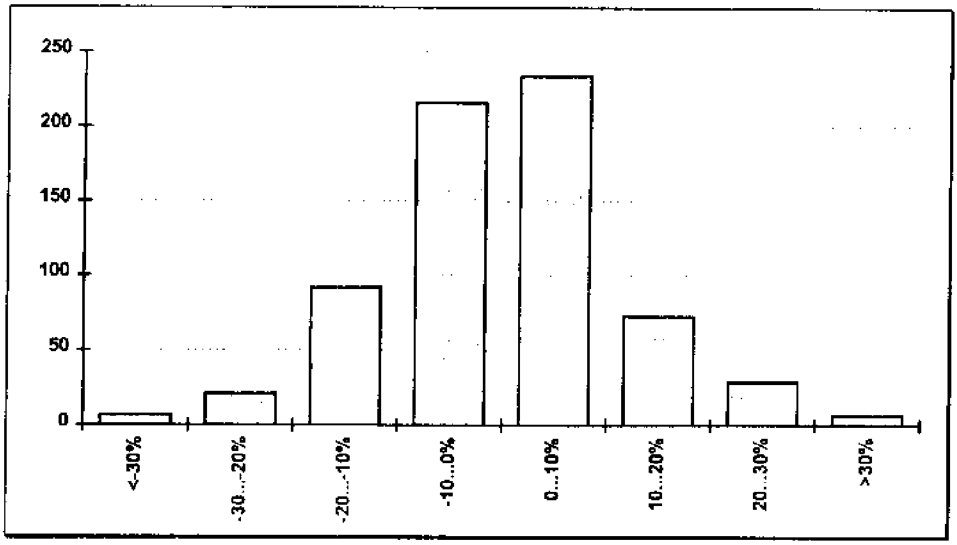
The average deviation between model test resistance and estimated resistance depends to a limited extent on the type of vessel. **Table 7** shows the average deviation and standard deviation for different types of vessels:

Table 7. Average and Standard Deviation for Different Types of Vessels

Type of Vessel	No of Tests	Average Deviation	Standard Deviation
Gas Carrier	56	+1.5 %	11.4 %
Tanker, Bulk Carrier	61	–0.5 %	9.5 %
Container Vessel, Refrigerated Vessels	37	--0.7 %	8.9 %
Multi-Purpose Container Vessel	165	+1.2 %	11.0 %
RoRo-Passenger- and Freight Ferry	80	+2.1 %	10.0 %
Cruising Vessels	58	-1.8 %	10.5 %
Passenger Ferry (small ships)	27	-4.1 %	15.2 %

Where L_{OS}/L_{WL}, L_{WL}/L_{PP} and D_P/T_A have been out of range during test computations, not the original value of the model itself has been used, but the corresponding limiting value instead. The distribution of average deviation of the new method from the results of the resistance tests, taking into account the above-mentioned limiting values, is shown in **Fig. 2**:

Fig. 2 Distribution of Average Deviation of (Model Test Resistance – Estimated Resistance)



The new method predicts much better not only the resistance of twin screw vessels, but also the resistance of single-screw vessels with large block coefficient ($C_B > 0.78$) and with small length/breadth ratios ($L_{PP}/B < 5.5$), **Table 6**:

Table 6. Average and Standard Deviation for large C_B and small L_{PP}/B Ratios

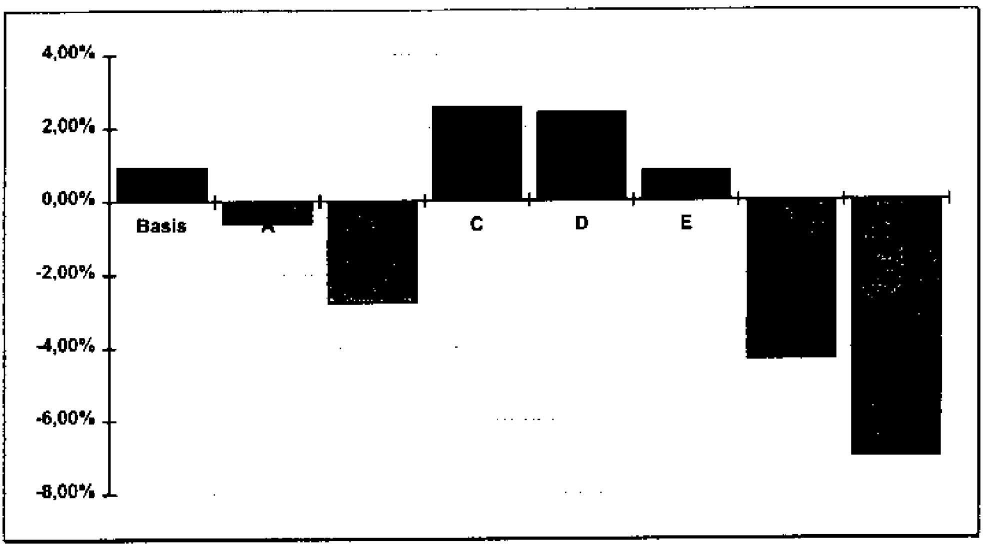
Method	$C_B > 0.78$			$L_{PP}/B < 5.5$		
	out of range	average deviation	standard deviation	out of range	average deviation	standard deviation
Holtrop-Mennen	20.0 %	+3.1 %	13.2 %	61.0 %	+12.9 %	19.7 %
Guldhammer-Harvald	72.2 %	+4.5 %	14.5 %	52.5 %	+12.3 %	17.7 %
Danckwardt 87	25.2 %	-3.2 %	13.4 %	50.0 %	+8.7 %	15.8 %
Lap-Keller	86.1 %	–3.0 %	9.5 %	74.6 %	+8.3 %	16.5 %
Series 60	81.7 %	–2.1 %	12.5 %	99.2 %	21.3 %	21.3 %
Hollenbach, no limits	0 %	+0.4 %	11.4 %	0 %	–0.6 %	13.2 %
Hollenbach, with limits	29.8 %	+1.4 %	10.4 %	38.6 %	+2.0 %	12.0 %

Improvements depending on the Number of Modifications

The database includes resistance tests with the initial form and, if modifications have been investigated, the final form of each vessel. Intermediate stages of modifications are not included in the database. In total 275 resistance tests of initial forms and 228 resistance tests of final forms are available. Determining the average deviation dependent on the number of modifications may give an indication of the effort which will be necessary to achieve a certain improvement in the resistance characteristic for a newbuilding project.

Initial forms on an average have a slightly higher resistance than predicted by the new method, the average deviation is +0.9%. Models which have been modified once (68 models, version A) have an average deviation of –0.6%, models which have been modified twice (42 models, version B) have an average deviation of –2,8%. Models, which have been modified more than twice and less than six times, have had insufficient resistance characteristics in the initial form and still have resistance characteristics in the final form which are below average (42 models - version C, 23 models - version D, 18 models - version E). Only models, which have been modified six times and more (13 models - version F and 22 models - versions G to T), are significantly better than average (–4,3% to –7,0%).

Fig. 3 Deviation from "Mean Resistance" dependent on Number of Modifications



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Passenger Ferry (small ships)	27	-4.1 %	15.2 %

"Minimum" Resistance Compared with the Fundamental Database

The new method for estimating a "minimum" resistance has been compared with the fundamental database. Computations have been performed for models on design draft only. For each model the average deviation covering the whole speed range of the test has been determined. **Table 8** suggests that the "minimum" resistance can reliably be estimated by the new method. Only eighteen models are better than estimated.

Table 8. Deviation from "Minimum" Resistance

Deviation	Single-Screw Vessels				Twin-Screw Vessels			
	without bulb		with bulb		without bulb		with bulb	
better than estimated	2	3%	4	2%	3	8%	9	5%
+0.0 % ... +2.5 %	2	3%	10	4%	5	14%	15	8%
+2.5 % ... +5.0 %	5	7%	17	7%	5	14%	25	13%
+5.0 % ... +10.0 %	13	19%	50	21%	10	27%	55	29%
more than +10.0 %	45	68%	160	66%	14	37%	84	45%
10% best vessels	minimum +5.9%		minimum +7.1%		minimum +0.0%		minimum +2.4%	
20% best vessels	minimum +8.5%		minimum +8.8%		minimum +5.8%		minimum +6.4%	

Within the range of the 10% best vessels all types of cargo vessels can be found, fourteen multi-purpose container vessels or container vessels, four tankers or bulk carriers, five roro-passenger- or freight ferries, five gas carriers, ten cruising vessels and four passenger ferries. The "minimum" resistance can reliably be estimated in the following range of main dimension ratios:

Block coefficient	C_B	0.525 ... 0,825
Length/breadth ratio	L_{PP}/B	5.00 ... 7.50
Breadth/draft ratio	B/T	2.50 ... 4.50

"Maximum" Resistance Compared with the Fundamental Database

The new method for estimating a "maximum" resistance has also been compared with the fundamental database. Computations were performed twice, at first the factor h_l of **Table 3** was used (which is equivalent to two times standard deviation), and secondly a factor equivalent to standard deviation itself was used, **Table 9**.

Table 9. Deviation from "Maximum" Resistance

Deviation	No of Models			
	using factor h_l (2 • standard deviation)		using factor $1+0.5(h_l-1)$ (1 • standard deviation)	
better than estimated	95.8 %	475	81.7 %	405
−0.0 % ... −5.0 %		12		54
−5.0 % ... −10.0 %		5		23
−10.0 % ... −20.0 %		4		11
less than −20.0 %		0		3

Validation against HSVA Models

The formulae for the "mean" resistance were validated against test cases of the Hamburg Ship Model Basin (HSVA) which were not included in the original database. Nineteen single-screw and six twin-screw ships were taken from projects carried out in 1996 and 1997. **Table 10** suggests the following conclusions:

- The new method shows a similar average error as the traditional methods, but better standard deviation, for single-screw ships on design draft.
- The new method predicts much better the resistance for single-screw ships in ballast condition.
- The new method predicts much better the resistance for twin-screw ships on design draft.

Table 10. Average and Standard Deviations for Test Cases of HSVA

	Single-Screw Ships design draft		**Single-Screw Ships** ballast draft		**Twin-Screw Ships** design draft	
	average deviation	standard deviation	average deviation	standard deviation	average deviation	standard deviation
Holtrop-Mennen	–0.5 %	12.8 %	6.3 %	16.1 %	5.8 %	18.4 %
Guldhammer-Harvald	0.8 %	11.0 %	10.5 %	17.9 %	11.2 %	19.2 %
Danckwardt 1987	–0.5 %	12.9 %	25.0 %	30.7 %	12.5 %	29.3 %
Lap-Keller	–0.8 %	12.8 %	27.9 %	32.9 %	14.0 %	23.4 %
Series 60	–1.0 %	11.6 %	37.3 %	42.7 %	15.2 %	23.3 %
New Method						
mean resistance	1.0 %	9.4 %	–0.2 %	11.2 %	3.5 %	13.3 %

Recommendations for Estimating Propulsive Factors

Hull Efficiency

The following formulae can be used to estimate the hull efficiency in model scale. The average length of the model is 6.5m.

For single-screw ships on design draft:

$$\eta_{H,\,model} = 0.948 \cdot (C_B)^{0.3977} \cdot (R_{T,\,\text{"mean"}} / R_T)^{-0.58} \cdot (B/T)^{0.1727} \cdot (D_P^2/B/T)^{-0.1334} \qquad (13)$$

For single-screw ships on ballast draft:

$$\eta_{H,\,model} = 1.055 \cdot (C_B)^{1.0099} \cdot (L/B)^{0.2991} \cdot (L_{WL}/L)^{-3.2806} \cdot (D_P/T)^{-0.2317} \qquad (14)$$

For twin-screw ships:

$$\eta_{H,\,model} = C \cdot (C_B)^{0.1202} \cdot (D_P^2/B/T)^{0.0285} \qquad (15)$$

The coefficient C for twin-screw ships is C = 1.125 for ships with shaft brackets and twin rudders, C = 1.224 for ships with twin skegs and twin rudders, C = 1.086 for ships with shaft brackets and single rudder, C = 1.096 for ships with shaft bossings and single rudder.

Thrust Deduction Factor

Experimental results showed no correlation between main dimensions and thrust deduction factor t. This depends instead on local form details and the propeller arrangement. Therefore, it is recommended to use an average value for t in the preliminary design stage, **Table 11**.

Table 11. Recommended Estimate for Thrust Deduction Factor t

Propeller	Draft	Appendages	Average	Standard Deviation
single-screw	design draft	---	0.190	20.4 %
single-screw	ballast draft	---	0.195	26.1 %
twin-screw	design draft	twin rudder, shaft brackets	0.150	29.1 %
twin-screw	design draft	twin rudder, twin skegs	0.186	22.4 %
twin-screw	design draft	single rudder, shaft brackets	0.130	36.0 %
twin-screw	design draft	single rudder, shaft bossings	0.113	34.5 %

Relative Rotative Efficiency

The relative rotative efficiency η_R does not correlate with the main dimensions either. η_R increases if the stock propeller of the model has a lower efficiency than the corresponding Wageningen B-series propeller. If for the power prognosis a Wageningen B-series propeller is used, η_R should be taken as

$$\begin{aligned} \eta_R &= 1.009 && \text{for single-screw ships on design draft} \\ \eta_R &= 1.000 && \text{for single-screw ships on ballast} \\ \eta_R &= 0.981 && \text{for twin-screw ships on design draft} \end{aligned} \tag{16}$$

Database-based Ship Trial Prognosis

Reference Vessels

The database used for the database-based method is a simple text-file (ASCII), which contains all relevant test data for each model: main dimensions, results of resistance test, results of propulsion test (thrust, torque, revolutions) and results of propeller open water test. To select reference vessels from the database the following main dimension ratios are calculated first:

$L_{FN}/\nabla^{(1/3)}$	Length / displacement ratio (referred to as L_{FN})	[m]
$L_{PP}/\nabla^{(1/3)}$	Length / displacement ratio (referred to as L_{PP})	[m]
C_B	Block coefficient	[-]
L_{PP}/B	Length / breadth ratio	[-]
B/T	Breadth / draft ratio at $L_{PP}/2$	[-]
$(T_A-T_F)/L_{PP}$	Trim / length ratio	[-]
L_{OS}/L_{PP}	Length over surface / length between $_{PP}$ ratio	[-]
D_P/T_A	Diameter propeller / draft aft $_{PP}$	[-]

The user can either select from three pre-defined search ranges 'standard', 'narrow' or 'wide' or can use a customized range of ratios for the search of reference vessels from the database. To speed up the search, there is a separate text-file for single-screw and twin-screw vessels and for vessels with and without bulbous bow.

Calculating the Resistance

The resistance test data of the selected reference vessels are scaled to the same displacement as the project vessel. For sets containing no resistance test data (for these models only propulsion tests have been performed) the resistance is estimated using the thrust measurements of the propulsion test and an estimation for the thrust deduction factor.

The scaled resistance data of the reference vessels are interpolated by spline-interpolation to the speed range of the project vessel. Furthermore the wind resistance and the resistance of appendages is added.

Calculating the Propulsion Factors

For complete datasets containing resistance test, propulsion test and open water test results the thrust deduction factor, the wake factor and the relative rotative efficiency are directly determined by evaluating the test results. Where no propulsion test data are available, these factors are estimated using the above-mentioned recommendations. Where no open water test results are available, a propeller efficiency according to the Wageninger B-Screw Series is assumed.

Thrust deduction factor and relative rotative efficiency are transferred unchanged to full scale. The mean effective wake of the reference vessel (in model size) is transferred according to Tanaka-Sasajima to full scale of the project vessel.

Calculating the Propulsion Prognosis

Using the resistance data and propulsive factors a propulsion prognosis is calculated, assuming a propeller efficiency according to the Wageninger B-Screw Series.

Comparison of Open Water Test Results of Stock Propellers with Wageninger B-Screw Series

For a propulsion prognosis in the preliminary design stage the Wageninger B-Screw Series is used in general. Comparison of open water test results of stock propellers with the Wageninger B-Screw Series showed on an average a slightly smaller propeller efficiency for the stock propellers. On the other hand, best stock propellers had a significantly better efficiency than the Wageninger B-Screw Series.

- The average efficiency of stock propellers at design speed is 2.8% less than the efficiency of a similar propeller according to the Wageninger B-Screw Series. The standard deviation is 3.5%.
- 23.5% of the stock propellers have a better efficiency at design speed than a similar propeller according to the Wageninger B-Screw Series.

The results of the evaluation suggested that the average efficiency of the stock propellers was slightly more dependent on the area ratio than a similar propeller according to the Wageninger B-Screw Series.

Furthermore it could be shown that propeller efficiency of the stock propellers depends on the diameter of the hub. Although the set of stock propellers included variable pitch propellers (large hub diameter) with the same propeller efficiency as a similar fixed pitch propeller (smaller hub diameter), the results suggested an average loss of propeller efficiency of 1% to 2% for the variable pitch propeller.

Best stock propellers had a better efficiency than the Wageninger B-Screw Series. The following Table 12 shows the maximum gain in propeller efficiency depending on advance coefficient J and pitch/diameter ratio P/D, which has been observed for the stock propellers. It has to be observed that grey areas are extrapolated and, therefore, believed to be uncertain.

Table 12. Maximum Gain for η_0 dependent on P/D and J

J	P/D								
	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30
0.10	*+1.0%*	0.5%	+0.4%	+2.9%	+6.4%	+10.2%	+13.6%	+15.8%	*+16.2%*
0.20	*+1.6%*	+0.4%	+1.0%	+3.0%	+5.7%	+8.6%	+11.2%	+12.9%	*+13.2%*
0.30	*+2.3%*	+1.4%	+1.8%	+3.2%	+5.2%	+7.4%	+9.2%	+10.5%	*+10.6%*
0.40	*+3.1%*	+2.4%	+2.6%	+3.6%	+4.9%	+6.3%	+7.6%	+8.4%	*+8.4%*
0.50	*+4.0%*	*+3.5%*	+3.6%	+4.1%	+4.8%	+5.6%	+6.3%	+6.7%	*+6.6%*
0.60		*+4.6%*	*+4.5%*	+4.7%	+4.9%	+5.2%	+5.4%	+5.4%	*+5.2%*
0.70			*+5.6%*	*+5.4%*	+5.2%	+5.0%	+4.8%	+4.5%	*+4.2%*
0.80				*+6.2%*	*+5.6%*	+5.1%	+4.5%	+4.0%	*+3.6%*
0.90					*+6.3%*	*+5.4%*	+4.6%	+3.9%	*+3.4%*

Practical Application

The new method for estimating resistance and propulsive factors as well as the database-based method are, among other methods for estimating resistance, used at Ship Design & Consult GmbH (SDC), which is a subsidiary of Germanischer Lloyd (GL) and Hamburg Ship Model Basin (HSVA), and at Germanischer Lloyd (GL) for different practical applications:

Ship Design and Consult GmbH

The new method is used at SDC during the preliminary design stage for resistance and propulsion prognosis for all kind of projects. SDC offers a wide range of services from initial design to delivery documentation.

Pre-Classification Services of Germanischer Lloyd

The new method is used in Pre-Classification Services of Germanischer Lloyd. In the early design stage it is helpful for the owner to know, whether or not the speed and the required engine output are acceptable. The new method helps to classify the projected speed characteristics as "optimized", "average" or "unsuitable" for example.

Research Projects of Germanischer Lloyd

The new method is used in several research projects, where ship resistance and propulsion have to be estimated. A current research project of Germanischer Lloyd is INTACT. INTACT stands for *"Intelligence Tracing of Ship Machinery Loads by means of Advanced Computerized Tools"*.

Acknowledgements

The idea to this study raised during my employment during 1989 to 1993 in the Department for Projects and Ships's Theory of Lindenau GmbH, a medium sized German shipyard located in Kiel at the Baltic Sea.

This study was a private research work and has been developed in close co-operation with the Vienna Ship Model Basin during my employment at Germanischer Lloyd in the years from 1993 to 1997.

I would like to take this opportunity to express my appreciation to all persons, who gave kind advice and assistance. Especially I would like to thank Prof. Dr.-Ing. Gerhard Strasser and Dipl.-Ing Richard Anzböck from Vienna Ship Model Basin, who made this research work possible.

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THE APPLICATION OF MULTI-OBJECTIVE ROBUST DESIGN METHODS IN SHIP DESIGN

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Abstract

When designing large complex vessels, the evaluation of a particular design can be both complicated and time consuming. Designers often resort to the use of concept design models enabling both a reduction in complexity and time for evaluation. Various optimisation methods are then typically used to explore the design space facilitating the selection of optimum or near optimum designs. It is now possible to incorporate considerations of seakeeping, stability and costs at the earliest stage in the ship design process. However, to ensure that reliable results are obtained, the models used are generally complex and computationally expensive. Methods have been developed which avoid the necessity to carry out an exhaustive search of the complete design space. One such method is described which is concerned with the application of the theory of Design Of Experiments (DOE) enabling the design space to be efficiently explored. The objective of the DOE stage is to produce response surfaces which can then be used by an optimisation module to search the design space. It is assumed that the concept exploration tool whilst being a simplification of the design problem, is still sufficiently complicated to enable reliable evaluations of a particular design concept. The response surface is used as a representation of the concept exploration tool, and by it's nature can be used to rapidly evaluate a design concept hence reducing concept exploration time.

While the methodology has a wide applicability in ship design and production, it is illustrated by its application to the design of a catamaran with respect to seakeeping. The paper presents results exploring the design space for the catamaran. A concept is selected which is robust with respect to the Relative Bow Motion (RBM), the heave, pitch and roll at any particular waveheading. The design space is defined by six controllable design parameters; hull length, breadth to draught ratio, distance between demihull centres, coefficient of waterplane, longitudinal centre of floatation, longitudinal centre of buoyancy, and by one noise parameter, the waveheading. A Pareto-optimal set of solutions is obtained using RBM, heave, pitch and roll as criteria. The designer can then select from this set the design which most closely satisfies their requirements. Typical solutions are shown to yield average reductions of over 25% in the objective functions when compared to earlier results obtained using conventional optimisation methods.

1. Introduction

Ships and other marine vessels are often large and complex and incorporate many interdependent systems. During the design of such vessels, operational and manufacturing considerations are included in the models used during the development of the design concept. One result of this approach is that the models are large and the measure of performance is usually multi-criteria.

Such complexity usually meant that when the models were used in concept design studies, they were decomposed and each element of the model optimised and then the sub-optimal solutions were aggregated to produce an overall optimal design.

Clearly such an approach resulted in designs which were generally not the true overall optimum. Recent work in robust design methods, Whitfield [1], and multi-criteria optimisation, particularly the use of Genetic Algorithms (GAs), Todd [2], provide the designer with effective design environments which avoid the necessity to decompose the design model. Such an approach enables practical and realistic models to be used during the earliest stages of the design process.

The following section describes a brief history of the robust design process, extensions to the process and the current state of the art. Section 3 details the key parts of the framework and how they are combined to produce a robust concept exploration tool. A description of the catamaran design problem is given within section 4. Finally the results are illustrated and discussed, and concluded in sections 5 and 6.

2. Background

Japanese industrialists identified that both product quality and the associated manufacturing design processes needed to be significantly improved in order to achieve a more competitive manufacturing industry. Consequently, Genichi Taguchi, a quality consultant, was given the task of developing a methodology to meet these requirements. Robust design methodology was established to improve quality and enable manufacture at low cost by making product and process performance less sensitive to variability in product materials and process environments.

Substantial research has been undertaken to enhance robust design methodology since Taguchi's work, particularly the statistical techniques used. Taguchi's methodology involved experimental design and statistical analysis. The approach to experimental design involved a product array which was comprised of a control array and noise array. In an experiment, each combination of the control array was considered with every combination of the noise array. Taguchi assumed that no interactions exist between control factors and hence a large number of control factors could be studied in a small experiment. In addition, Taguchi recommended that noise effects only be tested at two or three settings.

Taguchi's approach to the analysis of experiments involves categorising robust design problems into three distinct groups related to their objectives. These are smaller-the-better, nominal-the better and larger-the-better. The optimal factor settings are identified by maximising the signal to noise (SN) ratios, these being Taguchi's quality characteristic. Taguchi [3] used main effect plots and analysis of variance tables to determine factor settings that maximise SN ratios.

Chen et al [4] used Central Composite Design (CCD) as the main method for designing experiments and subsequently produced a quadratic response surface for use in the optimization process. Their method incorporates Taguchi's robust design principles. Chen utilised this robust concept exploration method for the determination of top level design specifications for the airframe and propulsion system of a high speed civil transport system. Chen also introduced the idea of modelling unknown design parameters, particularly common at the concept exploration stage, as noise factors. Chen defines the robust optimum as a flat region being close to the optimum whilst having least variation for deviations in the design parameters. The method initially involved classifying the different design parameters from knowledge of the overall design requirements. This information was then passed on to a DOE module which selected a suitable experiment design depending on the order of model required.

The experiments are then used by the simulation tools for evaluation. Finally "robust top-level design specifications" were produced from the response surface equations which were verified to demonstrate the suitability of the response surface. Welch et al [5] discuss the use of the combined array as opposed to Taguchi's product array as well as the use of CCD to reduce the number of experimental runs required to produce the response surface.

Although not strictly addressing the subject of robust design, papers by Engelund et al [6] and Unal et al [7] identify most of the issues arising during robust design and are useful examples of application at the concept design stage. The aim of Engelund's work was to produce a set of optimal design parameters for a space vehicle. A "baseline" concept for the vehicle was produced as a starting point. A small number of geometry parameters known to have a major influence on the aerodynamic characteristics were selected as design parameters. The objective of the analysis was to optimize the design parameters such that a minimum vehicle dry weight could be achieved whilst maintaining stability throughout several re-entry flight regimes. The optimization process was conducted for several different sets of constraints resulting from different mission profiles. A design was obtained that had a reduction of approximately 9% in the dry weight of the baseline concept whilst being stable throughout all the re-entry flight regimes.

The approach to robust design summarised by Alvarez et al [8] is similar to that described by Chen and Engelund. Initially, the engineer's judgement was used to establish the input factors and criteria. The authors used the Box-Behnken experimental design method due to the small number of runs enabling the evaluation of a quadratic response surface. Simulations were then undertaken and upon completion, response surfaces were generated using regression analysis to approximate the simulated results. Finally, a range of input factors were identified which met the different criteria conditions simultaneously.

3. Description of Methodology

A product's robustness is a measure of the variation in its utility experienced in a typical application. That is to say, the lower the sensitivity or variation in utility, the greater the robustness of the design. In this work, we consider robust design to be the process by which a design is produced in which changes in the selected parameters which define the optimum design have relatively little effect on the performance of the design, i.e. the behaviour of the selected design is insensitive to modest changes in the parameters.

The robustness framework was developed using the philosophy of Taguchi whilst incorporating state-of-the-art statistical techniques. The framework was decomposed into a series of modules which were created to handle particular aspects of the robust design process. The modules are currently combined to produce the framework as a single system, however future work will enable the modules to be used as separate entities. A modular representation of the robustness framework can be seen in Fig. 1, whilst the progression of the robust design process can be seen in Fig. 2a.

The framework facilitates the decomposition of the design problem into simulation tools capable of handling sub-requirements. The problem may consist of any number of related or unrelated simulation tools. The robustness framework has a tool management module which is responsible for ensuring that each simulation tool obtains the information required from the DOE module and also for transferring information between simulation tools within the framework. Simulation tools can be added into the framework providing that they have an associated capability interface. The capability interface consists of information regarding the parameters and criteria associated with the simulation tool, essentially being a description of what the simulation tool is capable of whilst providing necessary information to the DOE module.

Having decomposed the design problem, the designer then uses the DOE module to select the parameters used to define the design space. The design space parameters are defined as being input information to the simulation tools. Similarly, the designer can select any number of criteria which are regarded as being the output information from the simulation tools. The DOE module also enables the selection of the upper and lower bounds of the design space and the determination of the type of each parameter, i.e. control or noise. The objective for each criteria can also be selected as being either minimisation, maximisation or a target value.

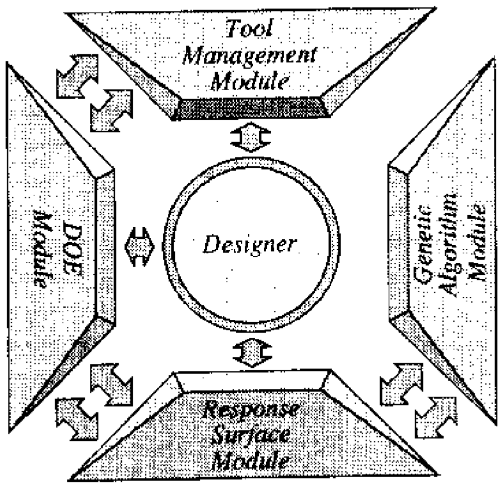

Fig. 1. Modular representation of robustness framework.

The DOE module is also responsible for designing the experiment to explore the design space. A point generator is incorporated within the DOE module which is capable of generating full and variable fractional factorial and Central Composite Designs (CCD). The full and fractional factorial designs are available for any order of problem, whereas the CCD is currently designed to be used for second order problems only.

Typically, the first run of the analysis uses a saturated fractional factorial design to provide the designer with an overview of the design problem. With this information factors can be removed from the analysis that are not considered to be significant. This technique relies upon the assumption that the main effects have greater significance than the interaction terms, hence the removal of the factor from the analysis does not have any consequence on the response surface generated. The designer can subsequently study the design problem without having to dramatically increase the size of the experiment. A second order response surface design can then be used with the significant factors to produce a representation of the design concept that has more detail than the first order model.

The DOE module then passes the potential design concepts to the tool management module for evaluation. Design concepts are evaluated sequentially, however research is currently being undertaken exploring methods of integrating the robustness framework with a design coordination system operating in a distributed computing environment to considerably reduce the time taken for concept exploration - see Fig. 2b.

Following the concept exploration stage, the response surface module uses the information obtained from the DOE module to produce a set of normal equations. If a criterion is dependant on a noise parameter the response surface module will produce two measurements for the criterion, one for the mean value, and one for the standard deviation using a similar philosophy as that used by Taguchi. The objective for the standard deviation criterion will be automatically set to minimisation.

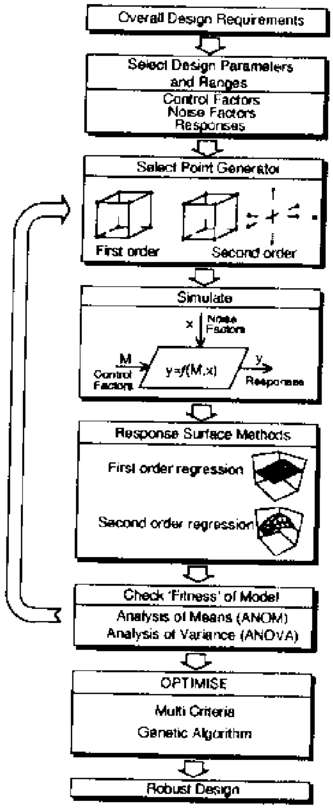

Fig. 2a. Robustness framework.

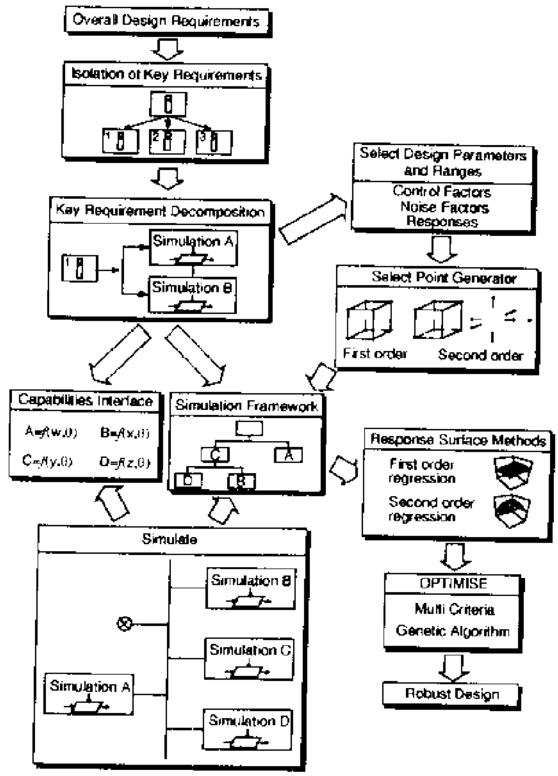

Fig. 2b. Design coordination system.

The genetic algorithm module then uses the response surfaces to quickly explore the design space and produce a Pareto-optimal set of solutions. The solutions are represented by a design concept with associated evaluations for the criteria. The designer can then select from the Pareto-optimal set the design that most closely satisfies the overall requirements. This selection process is currently undertaken manually although future developments will enable the selection to be guided by decision making processes.

4. Description of the Design Problem

A case study was selected with which staff in the Department of Marine Technology and the Engineering Design Centre have undertaken considerable work. The problem incorporates a single simulation tool which is capable of giving a number of measurements for the seakeeping of a catamaran.

The objective of the work is to explore the design space for the catamaran and select a concept which is most robust with respect to the selected seakeeping quantities for any particular waveheading.

The design space for the catamaran problem was defined by six control parameters and one noise parameter:

Control Parameters (Primary):	Hull length	L,
	Breadth to draft ratio	B/T,
	Distance between demihull centres	Hs,
Control Parameters (Secondary):	Longitudinal centre of buoyancy	LCB,
	Coefficient of waterplane	Cwp,
	Longitudinal centre of flotation	LCF,
Noise Parameter:	Waveheading	ϕ.

The seakeeping quantities selected here to be minimised are the peak values of the response amplitude operators, RAO, associated with heave, roll, pitch and the relative motion at the bow of each demihull as a function of all three motion quantities combined relative to the free surface elevation, $\zeta_{x,y}$, at the bow located at (x,y).

$$s_r = s_3 + y \cdot s_4 - x \cdot s_5 - \zeta_{x,y} \tag{1}$$

Criteria:	Maximum heave amplitude,	$\left\|s_3\right\|_{max}$
	Maximum roll amplitude,	$\left\|s_4\right\|_{max}$
	Maximum pitch amplitude,	$\left\|s_5\right\|_{max}$
	Maximum relative bow motion, RBM.	$\left\|s_r\right\|_{max}$

A diagrammatic representation of the design parameters and criteria for the catamaran design problem can be seen in Fig. 3.

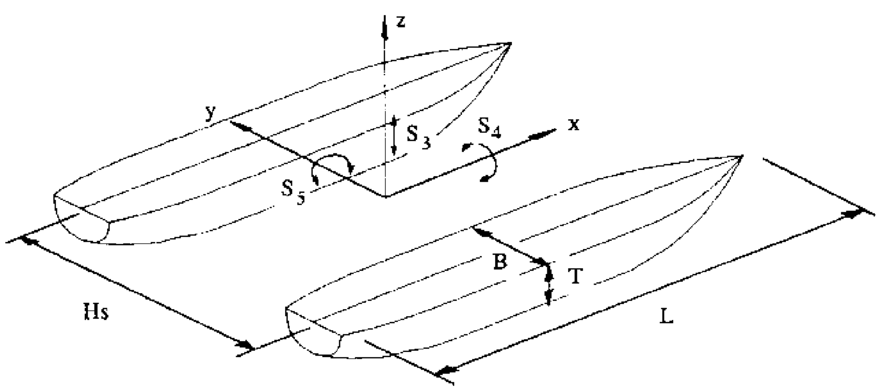

Fig. 3. Design parameters for catamaran.

Given this particular problem, the solution space would have eight dimensions; a mean and a standard deviation component for each of the four criterion, and would subsequently prevent the illustration of the results obtained from the optimisation process.

For illustrative purposes, an example was chosen which demonstrates the application of the methodology with respect to the relative bow motion only. A complete analysis, however, was also undertaken using all of the criteria to illustrate the ranges of designs produced and the trade-offs made during the optimisation process.

The design space was explored relative to a parent design and was expressed as a percentage change for the primary and secondary design parameters and in absolute terms for the noise parameter as shown in Table 1. The control parameters were given an offset, rather than having a range of ±10% and ±1%, to eliminate cancellation during solution of the normal equations from having a mid point at zero.

Table 1: Design Space for Catamaran Problem

Parameter	Type	Parent	Lower Bound	Mid Point	Upper Bound
ϕ	Noise		90	135	180
L	Control	104.0 m	-9%	+1%	+11%
B/T	Control	2.0	-9%	+1%	+11%
Hs	Control	31.0 m	-9%	+1%	+11%
LCB	Control	45.408	-0.9%	+0.1%	+1.1%
Cwp	Control	0.758	-0.9%	+0.1%	+1.1%
LCF	Control	43.306	-0.9%	+0.1%	+1.1%

5. Results and Discussion

The DOE module is capable of selecting a number of different DOE methods to enable the efficient exploration of the design space. In this particular example, the DOE module designed 79 experimental runs to be undertaken using the CCD method to enable the generation of a quadratic response surface.

The tool management module was then requested to execute the design algorithms to evaluate the potential design concepts. The design space as defined by the DOE module was subsequently explored in approximately 10 minutes using a Sun UltraSparc 10 workstation. Coates et al [9] produced a design coordination mechanism which can be integrated within this framework that enables the execution of design activity to be undertaken in a parallel and distributed manner which significantly reduces the time taken to explore the design space.

The results from the concept exploration stage were then used by the response surface module to construct the regression equations. A set of normal equations were produced using the method of least squares based upon the information generated from the concept exploration. These normal equations were then solved using Cholesky LU factorisation to produce the following regression equation for the relative bow motion as a function of the seven design parameters.

$$
\begin{aligned}
Y = {} & 3.6469 - 0.0786x_1 + 1.1386x_2 + 0.6558x_3 - 0.0876x_4 + 0.5590x_5 + 2.5014x_6 \\
& - 9.5733x_7 + 0.0003x_1^2 - 0.0107x_1x_2 - 0.0073x_1x_3 + 0.0005x_1x_4 - 0.0051x_1x_5 \\
& - 0.0283x_1x_6 + 0.1020x_1x_7 - 0.0007x_2^2 + 0.0025x_2x_3 - 0.0002x_2x_4 - 0.0361x_2x_5 \\
& - 0.0094x_2x_6 + 0.0176x_2x_7 + 0.0070x_3^2 - 0.0006x_3x_4 - 0.0165x_3x_5 + 0.0018x_3x_6 \\
& - 0.0175x_3x_7 - 0.0013x_4^2 - 0.0041x_4x_5 - 0.0077x_4x_6 + 0.0013x_4x_7 - 0.0814x_5^2 \\
& - 0.0375x_5x_6 + 0.2128x_5x_7 + 0.0273x_6^2 + 0.7284x_6x_7 + 0.1844x_7^2 \qquad (2)
\end{aligned}
$$

This regression equation is generated and used automatically within the robustness framework and hence, does not allow the manual removal of any insignificant terms. Future developments within the framework will, however, enable the automatic identification of insignificant regression equation terms and will subsequently prompt the user to enable their removal. The regression equation was used to produce the response surfaces seen within Fig. 4 for a waveheading of 135°. RBM was plotted against hull length and breadth to draft ratio for the parent *Hs*, as well as *LCF* and *LCB* for the parent *Cwp*. The values of RBM are obtained with respect to the parent design, hence increasing negative values indicate increasing desirability. The simulation tool was used to obtain results from the same points for comparison. The designer could manually select an optimal combination of hullform parameters based on the optimal individual combinations of primary and secondary parameters indicated from the primary and secondary design charts. This superposition of the optimal solution for each group has been found previously to provide an indication of the location of the global optimum, although not necessarily the optimal value for each parameter.

The primary and secondary parameter changes indicated in Fig. 4 are consistent with previous findings. The primary design chart indicates that an increase in *L* and *B/T* are of benefit. Similarly, for the secondary design chart, the conclusion of moving *LCF* forward and *LCB* aft would demonstrate further improvement.

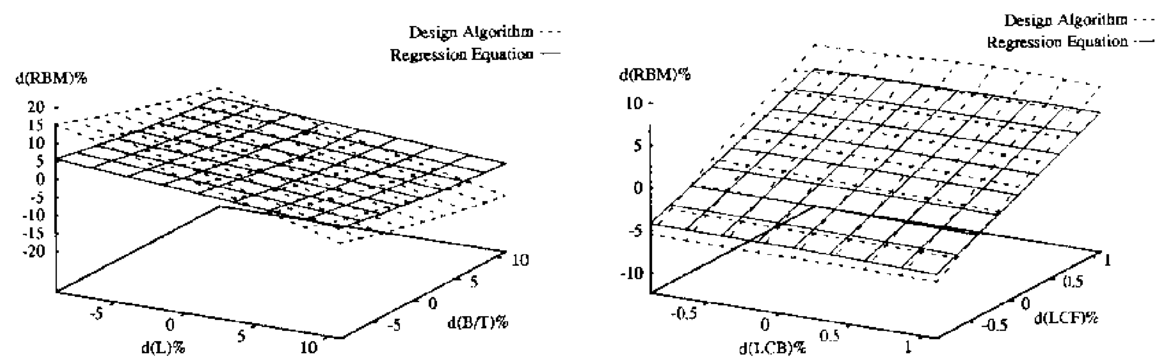

Fig. 4. Primary and secondary design charts.

The GA module conducts an evaluation of the regression equation for a number of different waveheadings and produces estimates for the mean and standard deviation of the relative bow motion. These criteria are then used to guide the GA to facilitate the selection of a Pareto-optimal set of designs. The Pareto-optimal designs can be seen within Fig. 5. For a full description of the GA used within this framework see Todd et al [10].

Fig. 5 represents 361 design concepts covering the range of values for the minimisation of both the mean (μ) and standard deviation (σ) components of the relative bow motion. It represents a range of designs having a low value of σ indicating a relatively flat region of the response surface, to designs having a high σ indicating a spiked region. The designer can subsequently make trade-offs between the designs to suit the characteristics required. Fig. 5 also indicates that the trade-off between the mean and standard deviation is linear. This is discussed by examining a number of different designs from within the Pareto-optimal set. Two designs were chosen as indicated by the points within Fig. 5 and represented in Table 2.

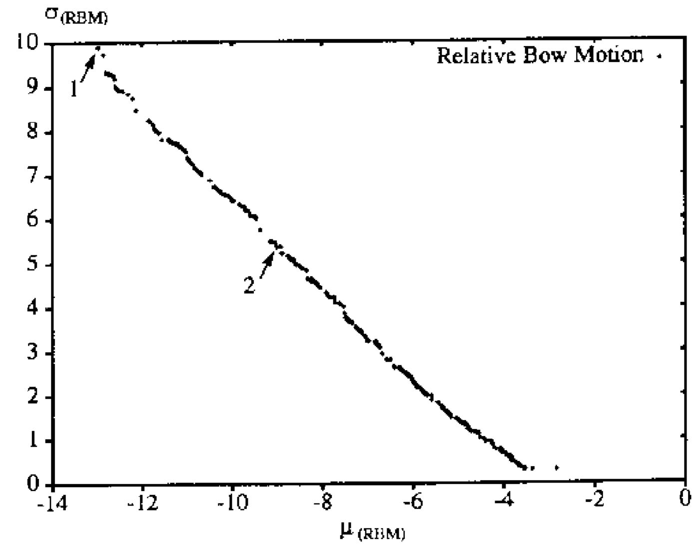

Fig. 5. Variation in mean and standard deviation for Pareto-optimal designs.

The simulation tool was subsequently used to evaluate the two designs with respect to the RBM by varying the waveheading between 90° and 180°. The results for these two designs can be seen in Fig. 6. The methodology can be seen to achieve average reductions of RBM of 19% for design 1. Fig. 6 indicates that the value for the standard deviation is due to the change in *d(RBM)* at 90°, having a higher value than over most of the range of waveheadings for both of the designs. The designs indicated either a detrimental change, or no change in *d(RBM)* around 90°. The lack of improvement for waveheadings approaching 90° is explained by the dominance of the roll component over the vertical component motions of heave and pitch.

Table 2: Designs selected for analysis.

Design	d(L)%	d(B/T)%	d(Hs)%	d(LCB)%L	d(Cwp)	d(LCF)%L	$\mu_{(RBM)}$	$\sigma_{(RBM)}$
1	10.68	9.52	4.56	1.03_{aft}	1.09	$0.89_{forward}$	-12.96	9.89
2	-0.70	8.38	10.84	0.95_{aft}	1.09	$0.88_{forward}$	-9.00	5.38

Despite design 2 having a lower standard deviation, suggesting that the design would be on a flatter region of the response surface indicating a greater robustness, it is evident that further reductions in *d(RBM)* can be obtained by selecting design 1.

The advantages of using such a methodology are such that the designer is faced with a set of Pareto-optimal designs which can be used within the selection process when further information is required regarding customer requirements. Trade-offs can subsequently be made within later stages of the design process whilst ensuring that the chosen design has optimal criteria.

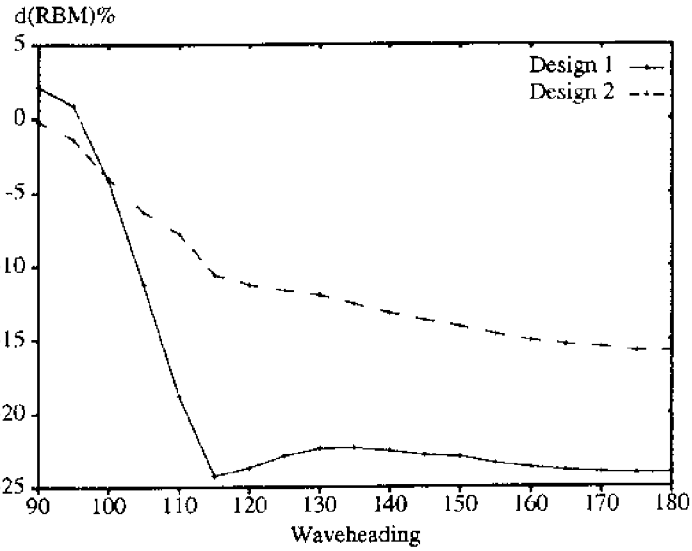

Fig. 6. Variation in RBM with waveheading for two Pareto-optimal designs.

Finally, the analysis was repeated using RBM, heave, pitch and roll as the objective functions. The experiments were repeated again using the 79 designs generated using the CCD technique. The design concepts generated were then used to build regression equations for the four objective functions. Future developments will enable the DOE module to store previous design concepts for possible reuse reducing the number of evaluations of the simulation tool and hence reducing the simulation time.

The GA produced a Pareto-optimal set of solutions consisting of 4372 designs having evaluations for the mean and standard deviation components of the RBM, heave, pitch and roll criteria. Future developments will enable the selection of suitable designs from the Pareto-optimal set using Multi-Criteria Decision Making (MCDM) techniques.

A number of interesting designs were selected manually and used for analysis. The values for the parameters for the designs can be seen in Table 3, whilst the results for the mean and standard deviation components of the criteria can be seen in Table 4.

Table 3: Designs selected for analysis.

Design	d(*L*)%	d(*B/T*)%	d(*Hs*)%	d(*LCB*)%*L*	d(*Cwp*)%	d(*LCF*)%*L*
3	10.86	9.71	-0.48	0.34aft	0.95	-0.68forward
4	10.85	-6.17	1.95	-0.53forward	-0.71	0.04aft

Table 4: Criteria for selected designs.

Design	$\mu_{(RBM)}$	$\sigma_{(RBM)}$	$\mu_{(Heave)}$	$\sigma_{(Heave)}$	$\mu_{(Pitch)}$	$\sigma_{(Pitch)}$	$\mu_{(Roll)}$	$\sigma_{(Roll)}$
3	-10.89	9.14	-20.80	18.00	-32.38	0.218	-17.42	0.47
4	-0.29	1.06	-2.59	0.41	-23.72	6.49	-25.25	0.70

The designs were selected on the basis that design 3 had considerable reductions in the mean values for RBM, heave and pitch, whilst design 4 had a considerable reduction in the mean value for roll. Table 3 suggests that designs having a high reduction in the roll criterion would be in a completely different area of the design space than for designs having high reductions in the other three criteria. This would indicate a trade-off situation which could be resolved by allowing the designer to identify the relative importance of each of the criteria and use an MCDM tool to facilitate the selection of a suitable design.

The simulation tool was used to evaluate the RBM, heave, pitch and roll criteria for design concepts 3 and 4. The results from these evaluations can be seen in Figs. 7-10.

It is evident from these Figs. that design 3 has considerably larger reductions in the RBM, heave and pitch criteria over most of the range of waveheadings when compared with design 4. Design 4, however, has a larger reduction in the roll criterion over the full range of waveheadings when compared with design 3. It is apparent that parameter changes of benefit to vertical motions and roll tend to conflict and occupy different regions of the design space, particularly with respect to *B/T* and *Cwp*.

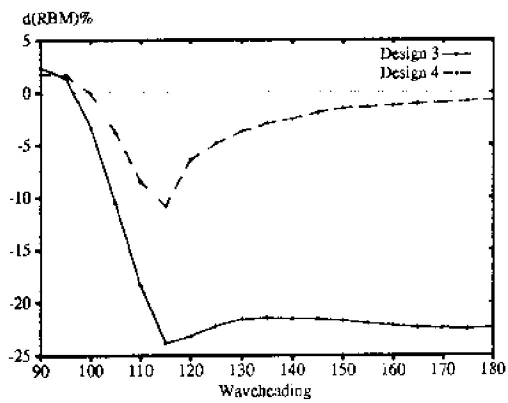

Fig. 7. Variation in RBM with waveheading.

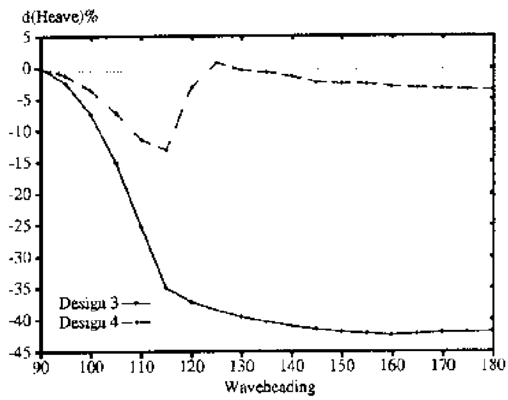

Fig. 8. Variation in heave with waveheading.

The primary and secondary parameter changes suggested to benefit RBM are consistent with solutions found previously by Sen et al [11] with the exception of the *LCB* position indicated. The LCB parameter was previously found however to be of little significance with respect to the RBM, hence suggesting that it is of little significance with respect to the other criteria - Whitfield et al [1].

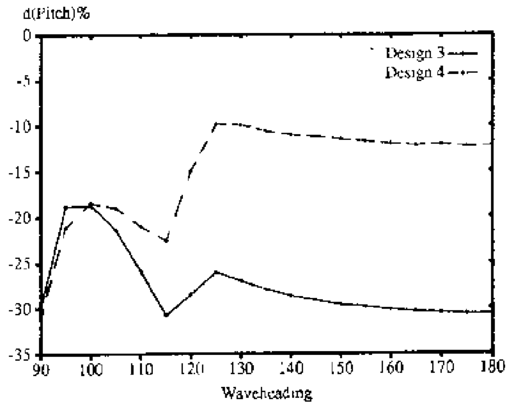

Fig. 9. Variation in pitch with waveheading.

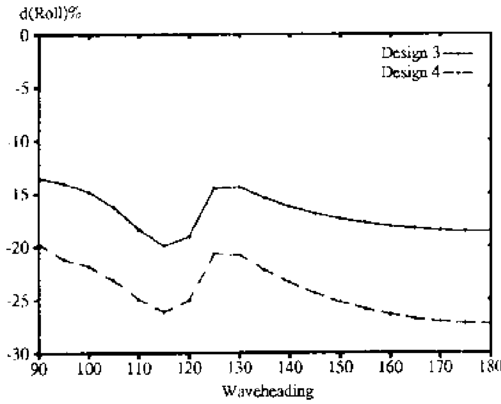

Fig. 10. Variation in roll with waveheading.

The results indicate that significant improvements can be found for several motion quantities simultaneously through identifying appropriate combinations of hullform parameters via the approach presented. The results further suggest that these improvements can be obtained in considerably less time than with other optimisation methods. The entire process of concept exploration and optimisation using this methodology took approximately 12 minutes for the single criteria case, and 30 minutes for the multiple criteria case. These times were obtained using a Sun UltraSparc 10 platform. The times compare favourably with the estimated time of approximately 66 hours using conventional methods, i.e. GA guided optimisation using the simulation tool.

6. Conclusions

The approach to robust design described in this paper has been shown to be efficient and effective when applied to a design problem in which the design model is complex and solutions computationally time consuming. Such models are common in the MTO field and further work is currently being undertaken to determine the range of applicability of the proposed robust design methodology.

The methodology has shown to work successfully within this particular problem, however the framework was designed and intended to be used with multiple dependent or independent simulation tools each analysing a particular aspect of the overall design problem. Such an implementation would further test the multiple criteria nature of this framework.

The software environment described in this paper has been developed by staff in the Newcastle Engineering Design Centre. There is comprehensive user documentation which guides the user through the methodology and application.

Acknowledgements

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PRELIMINARY DESIGN COMPUTER SYNTHESIS MODELING & COST ESTIMATING

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Abstract

The development of a system of computer-based ship design synthesis tools suitable for use in the early ship design process is described herein. The master synthesis program is a 32-Bit computer algorithm designed to be user-friendly through the utilization of a graphical user interface and data entry form. The underlying approach to design synthesis is achieved by iteration of a parent hull form by developing a family of derivative hull forms with variations on length, beam, and draft. The iteration is continued until a solution is achieved that provides adequate cargo deadweight, volume, or deck area, depending on the vessel type constraints. The solution ship also meets other design criteria including adequate stability, range, and speed. The algorithm contains a cost estimating module that utilizes material weight and construction labor hours developed by separate production process models for structure, machinery, and outfitting; each sensitive to shipyard specific facilities and production processes. The cost estimating module for structure is complete, and the mechanical systems and outfitting modules are under development. The synthesis program has been adapted and utilized for tankships and containerships. The modules for RO/RO passenger vessels and patrol craft are under development.

Introduction

Internationally, shipbuilders have achieved market domination in the design and construction of commercial ships principally through marketing designs optimized for production, series construction, innovative technology, new production processes, and improved facilities. In the marketing arena, some of the prerequisites for commercial customers in their shipyard selection process are quick response to inquiries, competitive pricing, and reliable delivery schedules. Any contribution to shipyard "tools," such as readily marketable standardized baseline designs, product or object data, and early stage cost and schedule estimating tools will assist in bidding competitively in the global marketplace and should be of significant interest and value.

M. Rosenblatt & Son, Inc. (MR&S) is developing a Portfolio of World Class Ship Designs for the Gulf Coast Region Maritime Technology Center (GCRMTC). The Portfolio consists of preliminary level designs that are supplemented with computer-based synthesis models capable of modifying the baseline designs to suit owner requirements. An early stage cost estimating module is part of each synthesis model, allowing for quick construction cost estimates and assessments of the impact of client-requested design changes on the construction cost.

Modules have been developed for containerships and tank ships. The architectures for RO/RO passenger ferries and patrol craft modules have been developed and formal coding will follow shortly. An equipment database has been developed utilizing catalog (object) information for the major machinery components, including prime movers, reduction gears, and diesel generators. A second database of parent hull forms is also part of the program. Because the program is a preliminary design tool, the inputs are kept simple. This allows for maximum flexibility in preparing or revising input data. Parametric input values can be readily modified to recalibrate the results for a new parent ship. The cost estimating module uses principal ship characteristics, provided by the synthesis program, and parametric equations to calculate the material weight and labor hours of a particular ship design. The module converts the material weight and labor hours to cost based on user inputs. The parametric equations are developed by separate production process models. The production process models are sensitive to shipyard specific facilities and production processes, allowing a broad range of user inputs. Presently the cost estimating module only considers structural costs, but will be expanded in the future to include outfitting and equipment costs. The following sections describe the nature of the ship design synthesis program and the production process model.

Design Synthesis Overview

Over the years, various formulations to synthesizing ship designs by computer analysis have been described in the literature. The basis of the underlying approach adopted herein is the interpolative design logic of Brower and Walker [1]. Essentially this makes use of a parametric hull form database and evaluates vessel stability range, and speed based on initial user input to seek a solution providing adequate cargo deadweight, volume, or area depending on the design constraints. An overview of the ship synthesis process is shown in Figure 1. As all databases and design parameters are user input, the approach improves on the reliability of the results when compared to a purely parametric approach.

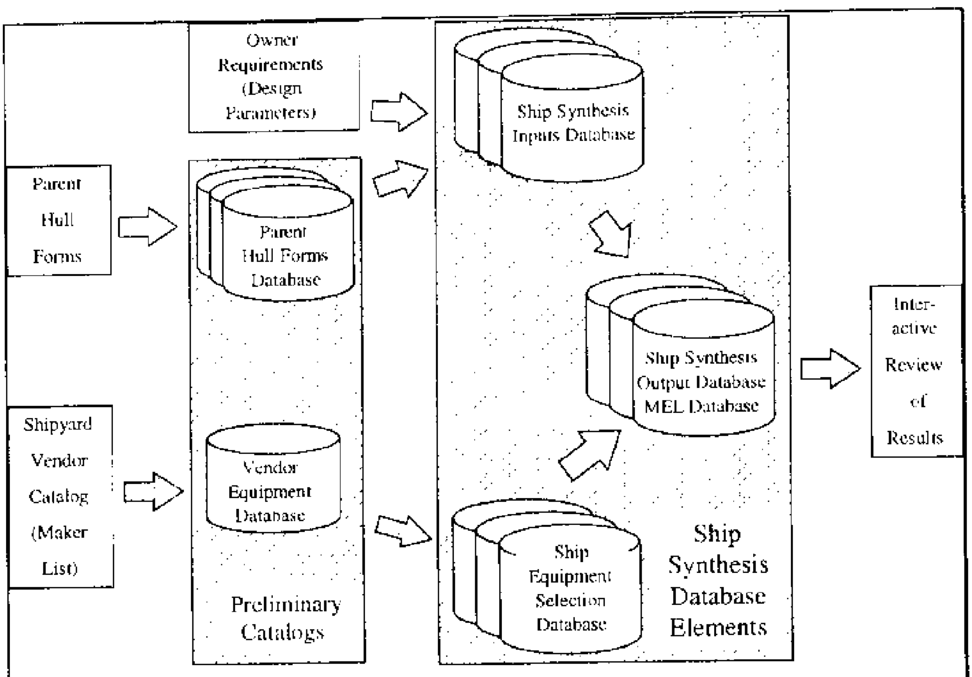

Figure 1 Data Structure for Ship Synthesis Model

Figure 1 shows that the ship design process is divided into four steps. The first step is the development of the preliminary databases defining Vendor Equipment and Parent Hull Forms (described in more detail below). The second step is the entry of the desired ship design parameters, including cargo deadweight, range, and speed. This is accomplished through a set of interactive computer-based forms. The user selects a parent hull form and the vendor equipment from the appropriate databases. The next step is the ship synthesis process in which the input parameters are used to generate a ship design that meets the given set of requirements. The final step is an interactive review of the results with a report generator. The user may then make changes to the ship design parameters and re-execute the synthesis process and again review the results. The process is continued until a satisfactory ship design is achieved.

The output from this ship synthesis model is a balanced, consistent ship design including:

- Cargo DWT
- Range and Stability Characteristics
- Number, Configuration, and Capacity of Tanks or Holds
- Hull Form Characteristics
- Light Ship Weights and Centers
- Variable Loads and Centers
- Design Speed and SHP
- Characteristics of Major Equipment
- Propeller P/D Ratio and Size
- Superstructure Size
- Structural Steel and Associated Labor Costs (Outfitting & Mechanical Systems later)

Vendor Equipment Database

The Vendor Equipment Database provides a means to define the various available types of equipment included in the ship design. The information in this database is derived from the Shipyard Vendor Catalog or Maker List. During the ship definition process, the user will select from the items entered into the Vendor Equipment Database to populate the Ship Equipment Selection Database. This allows the shipyard to qualify equipment prior to final definition of any given ship design.

The Vendor Equipment Database is the sole source of equipment data. This means that all equipment selected for a given ship design will be entered into the ship equipment database and is therefore available for use on any subsequent design. Maintenance of the ship equipment database is a natural part of the design process with new components continuously being added. The Vendor Equipment Database is divided into various parts based on equipment type. It presently includes engines, generators, and reduction gears and is being expanded to include other equipment data pertinent to cost, weight, and arrangement.

The Vendor Equipment Database scheme includes the following:

- For each engine series: series designator, description, manufacturer, RPM, specific fuel consumption, configuration, bore, stroke, VCG, and shaft height are stored. Number of cylinders, brake horsepower, weight, length, cost and man-hours for installation are included for each engine model within a given series.
- Similar data is stored for the generator sets.
- Reduction gear series data includes series and description. Size, maximum power rating, RPM, reduction ratios, and various physical parameters are stored for each gear model.

Parent Hull Form Database

A database of parent hull forms is included in the ship synthesis program. Like the equipment database, parent hull forms are entered into the database before beginning the ship design process. A different parent hull form will be entered for various combinations of ship type, size, and speed. The parent hull forms can be based on series data such as that developed by BSRA [2], or it can be any parent design with the desirable characteristics.

The database scheme of the parent hull forms includes LBP, appendage displacement, entrance angle, wetted surface, area of bulb, height of bulb centroid, wetted area of transom, stern identifier, and after body shape. Hydrostatic data is entered for the full load draft and a second lighter draft. In addition to the general characteristics, hull offsets are also entered. These hull offsets are stored as half-breadth dimensions for a matrix of waterlines at transverse sections. The hull offsets are used to determine cargo tank volumes and deck areas for the derivative designs. The program accepts files in the IDF format [3] and will be enhanced to accept General Hydrostatics (GHS) Geometry Files [4]. A viewing utility has been developed to allow the designer to view the hull form as in Virtual Reality Markup Language (VRML) format [5].

The user selects a parent hull form within a valid range of displacement and speed as a part of the definition of the ship design parameters. The computer program scales the offsets with independent multipliers for beam, depth, draft, and length to arrive at a scaled point design hull form. In addition, a number of hull form coefficients are also stored that are used to determine the ship hydrostatic characteristics and to estimate the powering requirements. The following parameters are entered and used, through linear interpolation, to determine ship hydrostatic properties at any intermediate draft:

- Beam at Waterline
- Volume
- Prismatic Coefficient
- Midship Coefficient
- Waterplane Coefficient
- Longitudinal Center of Buoyancy (+ Fwd of Amidships)
- Longitudinal Center of Flotation (+ Fwd of Amidships)
- Vertical Center of Buoyancy
- Moment to Trim One Centimeter
- Transverse BM (Transverse Metacenter minus Center of Buoyancy)

The following are entered for the hull at design draft.

- Appendage Displacement
- Entrance Angle (half angle from C.L., degrees. Will be estimated if blank)
- Wetted Surface Area (meters squared. Will be estimated if blank)
- Area of Bulb at Forward Perpendicular
- Height of the Centroid of the Bulb
- Area of Wetted Transom
- Stern Identifier
  - 1 single screw, conventional stern
  - 2 single screw, open flow stern
  - 3 twin screw
- After Body Shape Factor
  - -10 V-shape sections
  - 0 normal shape sections
  - 10 U-shape section

Design Synthesis Process

The Ship Synthesis Inputs Database can be initialized once the preliminary data is entered. The process involves entering the design parameters, defining the ship arrangement, design speed, hull depth, and house parameters. It also involves selecting a hull form from the Parent Hull Form Database, selecting the master equipment based on the Vendor Equipment Database, and selecting the modules used in the construction of the cargo block or the passenger areas. The ship synthesis process can begin once input data entry is complete and verified. Input includes the following parameters:

- Required Cargo, Speed, and Range
- Required Passenger Deck Area and RO/RO Deck Areas.
- Initial Beam and Maximum Beam; Initial Draft and Maximum Draft; and Initial Length for Synthesis Loop
- Number and Configuration of Cargo Tanks or Holds
- Double Hull Width (for tankships)
- Length of Machinery Box and Location of Collision Bulkhead
- Propeller P/D Ratio and Size
- Superstructure Size and Configuration
- Structural Cost Data (Outfitting & Mechanical Systems Cost Data to be accepted later)

The data initializing process described above includes the initial maintenance of the data in the Parent Hull Form Catalog, Vendor Equipment Catalog, and Cost Database. The ship synthesis input parameters are then entered including ship data, parent hull form selection, and master equipment selection. The ship synthesis process begins with the development of a ship design based on the initial beam, draft, and length. The Ship Synthesis process can then be conducted in the Fixed DWT Mode or the Fixed Dimensions Mode as described below.

The Fixed DWT Mode

This mode generates a matrix of 64 ships based on a user-selected range of beams, drafts, and lengths. The 3-dimensional matrix is progressively interpolated to arrive at a design with adequate cargo capacity, speed, stability, and range. This is the most powerful mode of operation requiring a full set of input parameters. The design process has been developed for weight limited ships, volume limited ships, and deck area limited ships. As shown in Table 1, there is a different principal quantity that is the overall driver of the design payload for each ship type. For the cargo ships this quantity is the revenue-earning portion of the vessel. For RO/RO passenger ferries, the useable deck area for passenger use and RO/RO storage area are the drivers. For the patrol craft, it is the portion of the vessel available for mission related activities that can be considered the cargo deadweight.

Table 1 Overall Ship Design Payload Driver

Ship Type	*Design Process*	Principle Design Quantity
Tank Ship	Weight Limited	Cargo Weight
Container ship	Volume Limited	Number of Containers
Ro/Ro Passenger Ship	Area Limited	Usable Deck Area
Patrol Craft	Area Limited	Usable Deck Area

The design process for area limited ships is shown in Figure 2. The synthesis process begins at the point shown in the diagram with the generation of the first point ship design. This design is created based on the initial values of beam, draft, and length.

The steps in the ship synthesis process include:

- Generation of hull offsets and calculation of ship displacement by application of specific values of beam, draft, and length to the parent hull form and hydrostatic data. At this point, the full load displacement is established.
- Calculation of powering requirements including EHP and SHP based on the hull form and propeller characteristics. The propulsion engine is selected based on the BHP required to meet the design speed and the details of the engine and reduction gear characteristics. Power requirements of shaft driven generators are included in the main powering requirements. Powering requirements are distributed over the number of main engines. The fuel required for range is calculated based on the SFC of the selected engines. The resistance and powering algorithms were adapted from the University of Michigan Power Prediction Program (PPP) by M. G. Parsons [6] which is based on the powering regression analysis developed by Holtrop [7][8].
- Calculation of the cargo DWT is derived from the dimensional hull form defined above and the location, length, and arrangement of the cargo block. Calculations are performed for varying ship types as follows:
  - **Tankers:** Tank volumes, cargo deadweight, and centers are calculated based on double hull dimensions and tank definitions. Cargo tank DWT is calculated on volume and density of cargo.
  - **Containership:** The number of containers in each hold is calculated based on hold definitions, container size and clearances, and existence of hatches. Cargo DWT is calculated on number of TEU and container weight.
  - **RO/RO Passenger Ships:** The available area in the holds and on the decks for seating, cabins, entertainment, or vehicles is calculated based on hull form and superstructure definition. Cargo DWT is calculated on area allocation and weight per passenger, vehicle, or space.
  - **Patrol Craft:** The available area and payload is based on hull form and superstructure definition.
- Fuel capacity is calculated based on a weight balance. Fuel capacity is equal to full load displacement less light ship, cargo deadweight, and other variable loads.
- Analysis of ship stability is conducted based on GM/beam ratio for full load departure and ballast arrival conditions.
- Calculation of structural cost (if selected). The selected modules are modified to reflect the arrangement and size of the subject ship. Labor hours and weight of steel are calculated.

Once the characteristics of the ship with the initial beam, draft, and length are calculated, the process is repeated twice more: the second time for an intermediate value of beam and the third time for the maximum value of beam. Draft and length are kept constant during this process. The resulting three ship designs are interpolated based on their stability characteristics to arrive at a solution beam that will provide adequate stability. A fourth pass through the synthesis process is then conducted to ensure a consistent set of parameters for this solution beam. At this point, a ship design has been developed based on the initial values of draft and length with a beam that provides adequate stability. This design was based on synthesizing four ships with four different beams. This design has the

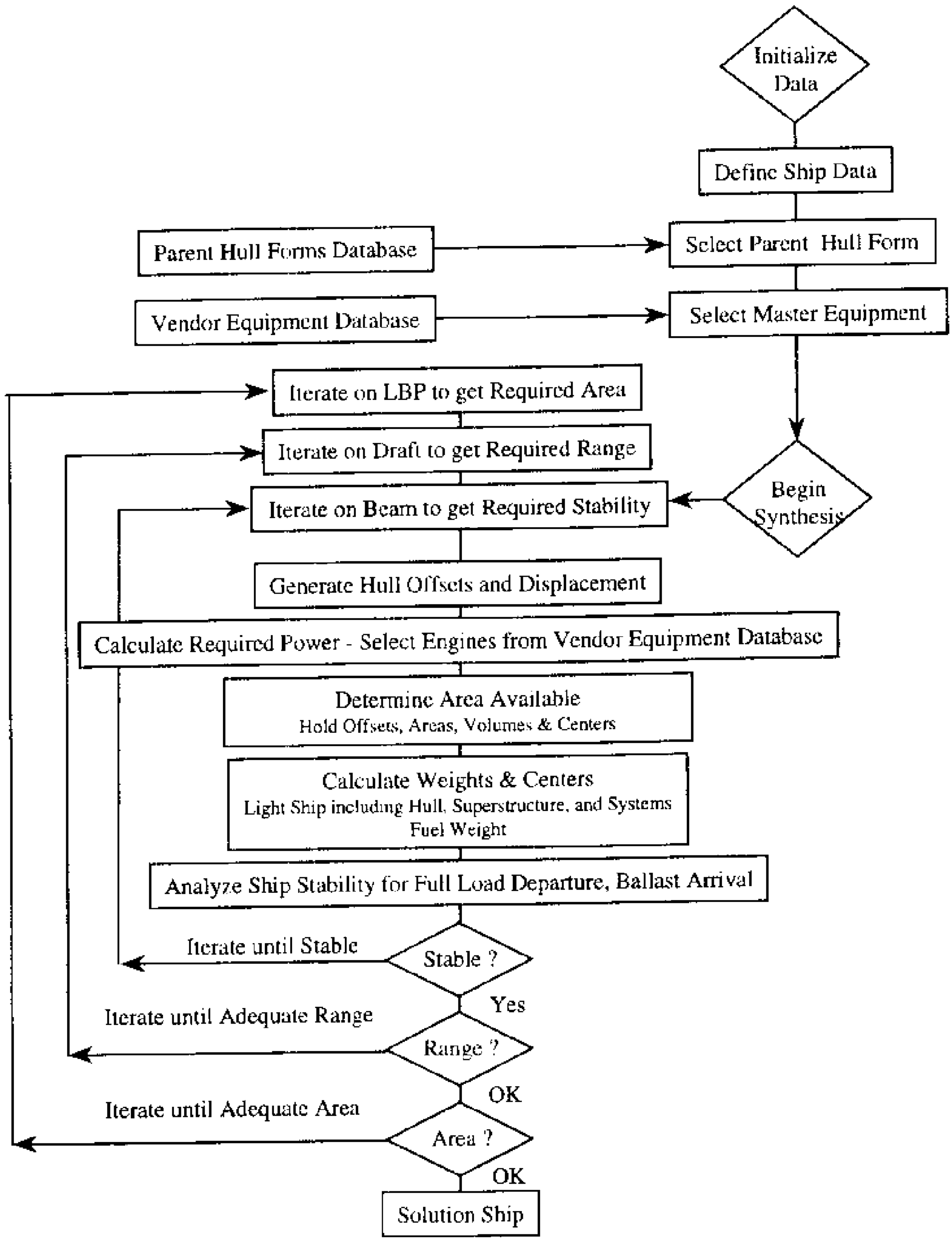

Figure 2 Ship Synthesis Functional Flow for Area Limited Ship

required transverse stability, correct superstructure configuration, required number and configuration of cargo tanks or holds, correct hull form, and correct engines to make design speed. However the design does not necessarily carry adequate fuel, nor does it necessarily carry the required cargo deadweight.

In order to arrive at a ship with adequate fuel capacity, it is necessary to repeat the beam/stability synthesis cycle three more times: the second time for an intermediate draft and the third time for the maximum input draft. These results are then interpolated on fuel capacity to select a draft that allows the ship to carry adequate fuel. A final pass is then made through the synthesis loop to ensure a consistent set of parameters for this solution beam and draft. The resultant design is based on synthesizing 16 ships with four different drafts and four different beams. At this point, a ship design has been developed based on the initial values of length with draft that provides adequate range and beam that provides the required transverse stability. The design also has the correct superstructure configuration, the correct cargo configuration, correct hull form, and installed engines that allow it to make design speed. However, the design does not necessarily carry the required cargo deadweight.

In order to arrive at a ship with the required cargo deadweight, it is necessary to repeat the draft/range and beam/stability synthesis cycles three more times with different lengths. These results are progressively interpolated on cargo DWT to select the required length. A final pass is then made through the synthesis loop to ensure a consistent set of parameters for this solution length, beam, and draft. It can therefore be seen that this final design was based on synthesizing 64 ship configurations with 4 different lengths, four different drafts, and four different beams. The results can be reviewed through the interactive process described below. During the ship synthesis process it is possible that the selected range of input parameters will result in a ship design that does not meet the requirements. In this instance, the program will warn the user that the input parameters failed to achieve a design that simultaneously meets all requirements. The designer will then revise the input parameters and re-run the synthesis.

It should be noted that the synthesized ship that results from this process is not necessarily the lowest cost ship. It is likely that a number of ships will be synthesized until the final selection is made. For instance, the hull depth is fixed throughout the synthesis process. A complete analysis of the solution ship design should include repeating the ship synthesis process for a range of depths with all other parameters kept constant. Deeper drafts will result in shorter ships with higher fuel requirements. The cost module under development will allow for a more complete analysis. Likewise the effects of employing different types of prime movers (slow speed diesel vs. geared medium speed diesel), or use of shaft driven generators vs. motor-generators can also be evaluated by conducting a number of ship designs. All of these designs can be kept in the database as variants on the original configuration allowing quick refinements and final selection.

Once the ship synthesis process is completed, the results are entered into the Ship Synthesis Output Database. The contents of this database can be reviewed through interactive forms. These forms include summary and detailed reports. The detailed reports show all of the characteristics of the subject design, including cargo tanks or holds, propulsion equipment, auxiliary equipment, master equipment list, and deckhouse characteristics. A detailed weight report is also available. These results can be reviewed on the screen or printed. Review of the results of a single synthesis can be used to revise the input parameters and conduct another synthesis until the resultant ship meets all of the design requirements and cost considerations. If the user would like to freeze a ship design, the "Save As" button can be used. This will create a copy of the selected design and allow the user to continue to change ship characteristics on a separate set of inputs.

Finally the program can be manipulated to consider cases where primary dimensions (length, beam, or draft) are limited by external requirements such as dock length, navigational drafts, or lock size. The program will independently restrain these dimensions. This will result in a synthesized design able to operate within a limited trade.

Fixed Dimensions Mode

This mode is used to determine the transverse stability, cargo DWT, range, and design speed of a point design with given length, breadth, and draft. This mode results in a single pass through the primary synthesis loop. The results are stored in the Ship Synthesis Output Database. This mode can be used to calibrate the synthesis program against a known ship design. Through the use of adjustments to the parametric coefficients the synthesis model can be re-calibrated to any baseline design. Once adjusted, the fixed deadweight mode can be used to synthesize ships with characteristics that differ from, but are consistent with, the baseline design.

Lightship Weight Estimating

Estimating the lightship weight is an integral part of the Ship Synthesis Model, and accurate results are crucial to the design process. Therefore it is important to have an understanding of the estimation process and the ability to customize the parametric equations in order to most accurately depict the subject ship. Estimates of weights and centers (Figure 2) are made by three different methods as explained in the Lightship Weight Estimating Theory Manual:

- **Manufacturer Specifications**: Major ship components such as the engines, generators, and reduction gears are selected from the Vendor Equipment Database in the Synthesis Model. Included in the Vendor Equipment Database is weight and center data.
- **Ratiocination**: Some weight groups can be accurately estimated by scaling from a similar vessel. A table of parent ships' weights has been created in the weight estimating database.
- **Linear Regression**: Weight data from previous vessels is plotted versus pertinent ship characteristics. A regression curve representing weight coefficients is generated in the Synthesis Model.

These weight computations are defined in workbooks containing a series of computer spreadsheets. Each workbook begins with a sheet summarizing the weight data for that group. Group-wide scalars are used to modify the weight and centers for the entire group. The second page of each group is a listing and brief description of all the variables used in the calculation of this weight group. Items for user input, such as vessel characteristics, are boxed. On the right side of the page there is a listing of ALTVALs, the coefficients used to modify equations in the Synthesis Model. There are three categories of ALTVALs in the Lightship Weight Estimating Theory Manual:

- Adjustment Coefficients: These are used to adjust individual weight items and centers and can be modified on each weight item sheet.
- Parent Ratio Coefficients: These are ratios derived from parent ships. They can only be changed in the Parent Ship Table. However, the adjustment coefficients above provide the ability to refine individual weight items estimated with ratios.
- Regression Coefficients: These numbers are the coefficients used in the plots of the ship data. They can be modified on the sheet for each weight item.

The third page of each workbook is a listing of the parent ship data used in the ratiocination for that weight group. This data is read from the Parent Ship Table in the Master Ship Weight Database. For each weight group, only one parent ship can be used. It is assumed that if a parent ship approximates one weight item in a group, it will approximate the other weight items. The fourth and following pages in each workbook describe specific weight items. For weights estimated from manufacturer specifications or scaled from parent ships, the data for the equations is taken from the second and third pages of the workbook. For weights estimated by linear regression, a table and graph are provided. The user may enter a ship number, and the corresponding data from the Parent Ship Weight Database will be automatically filled into the table. The data will be plotted on the graphs. If the user would like to adjust the characteristics of the fitted line to include or exclude a particular data point, that may be done.

The weight estimating spreadsheets draw upon a database containing tables for parent ships, as well as tables of weight data for regression analysis. The database is linked to the spreadsheet so that as additional ship weight information becomes available and is entered into the database, the coefficients for the equations in the Synthesis Model can be recalculated using the spreadsheets. Figure 3 represents the structure of the weight estimating database.

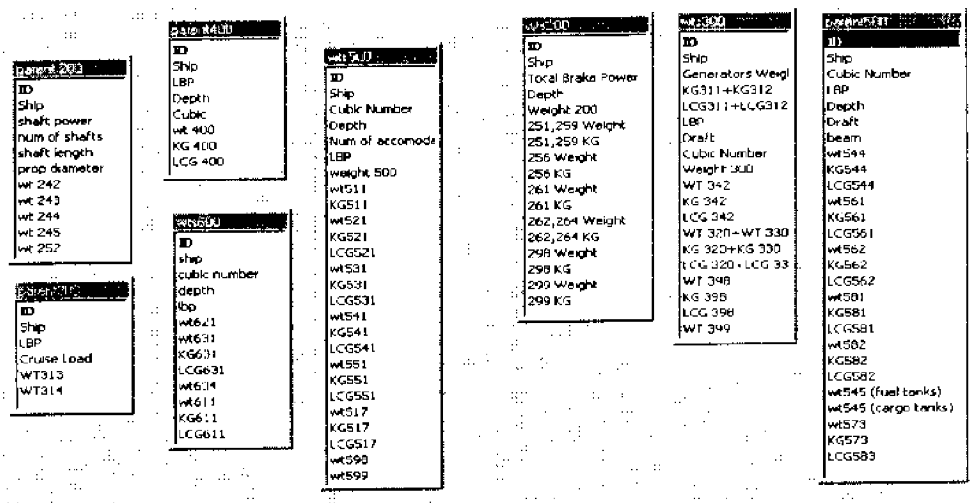

Figure 3 – Weight Estimating Database Structure

Cost Estimating

An essential part of obtaining the most benefit from the rapid design development possible with ship synthesis programs is to develop reliable cost estimates for the vessels with the same rapidity. As costs are so dependent on material and labor hours, which themselves are dependent on shipyard processes and vessel characteristics, it is essential that any cost estimating technique capture these features.

Cost Algorithm

The cost module uses simple parametric equations to convert the cost of a baseline ship to that of any new ship created by the synthesis module. The equations allow the cost of the new ship to be calculated quickly. While the parametric equations used are general, the coefficients are unique to the build process and the shipyard. The coefficients are developed using the production programs. The production program for structure is complete; the programs for mechanical systems and outfitting are being developed.

The total cost of the ship is the summation of the major components of the ship for which production programs are developed, plus the cost of major propulsion equipment as shown below. Major propulsion equipment cost, including procurement and installation will be added in directly from the Ship Equipment Selection Database.

$$\text{Total Cost} = \sum_{i=1}^{n} \text{Component Cost}_i + \sum_{j=1}^{m} \text{Major Propulsion Components}_j$$

The component cost will be calculated by multiplying the labor hours and amount of material of the component by labor rates and material costs. The labor rates and material costs are input by the user. The labor hours and amount of material of a component are calculated by multiplying the labor hours and amount of material of a subcomponent, a portion of a component, by ratios. The production program is used to determine the amount of material and labor hours required for the subcomponent. The ratios are calculated using the production program results and an independent cost estimate for the baseline ship. For baseline ships that have been built, return cost data can be used instead of a cost estimate. The production programs capture the shipyard specific build strategies and costs. This method is intended to capture shipyard specific production costs while minimizing the design and production planning efforts. The method is expressed in the following equations:

$$\text{Component Cost} = \text{Labor Hour}_{\text{Subcomponent}} \times \text{Labor Hour Rate} \times R_{LH} + \text{Material}_{\text{Subcomponent}} \times \text{Material Rate} \times R_M$$

Where :

$$R_{LH} = \frac{\text{Labor Hours}_{\text{Component}_{\text{Baseline}}} (\text{Baseline Cost Estimate})}{\text{Labor Hours}_{\text{Subcomponent}_{\text{Baseline}}} (\text{Production Program})}$$

$$R_M = \frac{\text{Material}_{\text{Component}_{\text{Baseline}}} (\text{Baseline Cost Estimate})}{\text{Material}_{\text{Subcomponent}_{\text{Baseline}}} (\text{Production Program})}$$

The production programs will also be used to derive the cost equations used to modify the subcomponent parameters to reflect a change in principal characteristics of the ship. Following the same general build strategy used to calculate the original subcomponent, a subcomponent modified for a change in the ship characteristics is input into the production program. The material costs and labor hours are then plotted versus the ship characteristic. This process is then repeated for various changes in the ship characteristics. The cost equations are derived by regressions of the resultant plots with the ship characteristics as variables. This is repeated for all of the principal characteristics. The total change is the algebraic sum of the changes in each characteristic as shown:

$$\text{Material}_{\text{Subcomponent}} = \text{Material}_{\text{Subcomponent}_{\text{Baseline}}} + \sum_{i=1}^{n} \mathfrak{Z}_i (\text{Ship Characteristic} - \text{Ship Characteristic}_{\text{Baseline}})$$

$$\text{Labor Hours}_{\text{Subcomponent}} = \text{Labor Hours}_{\text{Subcomponent}_{\text{Baseline}}} + \sum_{i=j}^{m} \mathfrak{Z}_j (\text{Ship Characteristic} - \text{Ship Characteristic}_{\text{Baseline}})$$

Where: $\mathfrak{Z}_i$ and $\mathfrak{Z}_j$ are the derived cost equations.

For example, the structural production program is used to determine the labor hours and steel weight of the cargo block based on a specific build strategy. The cargo block is then changed to represent different ship sizes. Based on these changes, cost equations are developed for the labor hours and steel weight of the cargo block. The results of the cost equations, labor rates, and unit steel costs are used to calculate the build cost of the hull.

One of the underlying assumptions of this method is that the hull and cargo block would be built in a similar fashion. In addition, any productivity gains realized by using a new build strategy to build the cargo block would also be realized in the bow and stern of the hull. Changes are assumed to affect the cargo block, bow, and stern all in the same way. Finally, the process assumes changes affect cost independent of each other. All of these assumptions become less true as the design moves farther away from the baseline design.

Production Program

The labor hours and material requirements of a subcomponent are estimated by identifying all of the discrete work processes and quantity of work to be done in each process. The quantity of work is then multiplied by a shipyard-specific process factor, to determine the labor hours required accomplishing each work process. The work breakdown follows the approach presented in NSRP Report 405 [9]. MR&S had previously applied this approach to the evaluation of the producibility of alternative structural concepts for double hull tankers [10]. The steps in the process are as follows:

1. Select the design feature (block or module) to be analyzed.
2. Identify the trades required to perform the work.
3. Identify the shipyard work process, which would be used in the production of the design feature.
4. Determine and apply the engineered standards for each work process.
5. Apply a factor to reflect the increased difficulty of performing the work at a stage other than the ideal stage on which the standard is based.
6. Apply a factor for the support labor hours required.
7. Total the labor hours and material requirements for constructing the design feature (block or module).

Essentially, steps 1-7 are accomplished in a spreadsheet-based production analysis tool with the resulting output obtainable for any product defined in the vessel build strategy.

At this time, the production analysis tool has been developed for structure only. The structure production program calculates the plate weight, the stiffener weight, and the labor hours required to build structures. The program consists of a two-worksheet EXCEL workbook. The first worksheet physically describes the structure. Every piece of the structure is input into the worksheet as either a plate or a stiffener. Both rectangular and triangular plates may be entered. In both cases, all of the outer dimensions of the plates and the thickness are entered. Then a weld is designated for each edge. Weld designation includes: type (butt or fillet), method (automatic or manual), and manual welding orientation (downhand, overhead, or vertical). Then the work stage is designated for each of the welds. There are seven work stages from stage 1 (in shop fabrication) to stage 7 (waterborne pier side). Similar information is input for stiffeners except that the type of stiffener is also inputted. There are five types of stiffeners programmed into the worksheet: flat bar, angle, tee, bulb flat, and a stiffener made up from two flat plates. The first worksheet calculates the plate weight, stiffener weight, the average thickness of the pieces in the module, and the weld length of all the welds. The first worksheet also subdivides and totals the weld length for each unique combination of type, method, orientation, and work stage.

The second worksheet calculates the labor hours for building the structure based on the information in the first worksheet and some additional process information derived from the build strategy. The work process is broken down into ten categories:

- Obtain Material
- Flame Cutting
- Edge Pre/Grinding
- Shaping
- Fit up & Assembly
- Machine Welding
- Manual Welding
- Marking
- Handing
- Rework

A process factor based on the thickness of the material is multiplied by a work unit to obtain the labor hours required for each of the ten work process categories. The process factors can be altered to suit any shipyard.

The major advantage of cost estimating based on work processes is that there is a direct relationship between work process and labor required. By definition, a work process is performed by labor and takes a finite amount of time. A direct relationship does not exist between the hull weight and the labor hours to produce the hull. Estimates not based on direct relationships may yield false answers. Assume that it was desired to minimize the cost of a stiffened plate in a transverse bulkhead and that the cost, labor, and material were estimated solely on the bulkhead weight. For this example, one method to reduce weight and the associated cost would be to reduce the spacing between stiffeners. As the spacing was reduced, the stiffeners would become smaller and more numerous. The plate would become thinner. These changes would result in a lower stiffened plate weight and a corresponding lower cost; however, the amount of actual work required to fabricate the stiffened plate increases as stiffeners are added to the plate. While this cost estimating method lowers the required labor hours, as weight decreases, the actual required labor hours increases with each additional stiffener.

Another advantage of cost estimating based on work process is that it accounts for changes to the work process. Labor hours estimated from physical parameters do not change when the work process is changed. The amount of material in a hull module is the same whether it was welded manually or automatically. Yet the cost of automatic welding is significantly lower. Physical parameters cost estimates do not take into account improvements in productivity due to shipyard production improvements.

World Ship Price Predictor

Before a shipyard can begin to examine its own capabilities to build a vessel, it is necessary to know approximately what price the vessel would bring on the global market. The World Ship Price Worksheet allows the user to determine a Rough Order Magnitude (ROM) ship price based upon trade type and ship size. With this price and information on the yard's capabilities, a determination of whether or not this vessel type is profitable and warrants further study can be made. The objective of this tool is to estimate the price, not cost, of a ship using few input variables. Fewer inputs reduces the tool's ability to capture various design characteristics, but this is acceptable as it is intended for early stage, high level use.

Information on the dimensions, speed, capacity, power, and new build price of recently constructed vessels was obtained for a large population of ships primarily taken from the Fairplay Encyclopedia of Shipping [11]. This data was examined for consistency, and the prices were converted to 1997 dollars. The parametric weight data was developed and combined with ship price using a linear independent regression to fit the existing data. A worksheet for the vessel information was created in a spreadsheet. The equations were then programmed into a separate module using Visual Basic for Applications. Operation of the World Ship Price Worksheet is straightforward. The user must first select the ship type of interest from the list on the right. The available ship types are:

- Tanker
- Containership
- Bulk Carrier
- Passenger Ship
- Dry Cargo
- RO/RO

The user must then enter the length, beam, depth, draft, and speed of the subject vessel. Installed horsepower may be entered or the program will estimate if "0.0" is entered. Once the inputs are complete, the user presses the "Compute Price" button and the estimated price will be displayed. The World Ship Price Spreadsheet is shown in Figure 4.

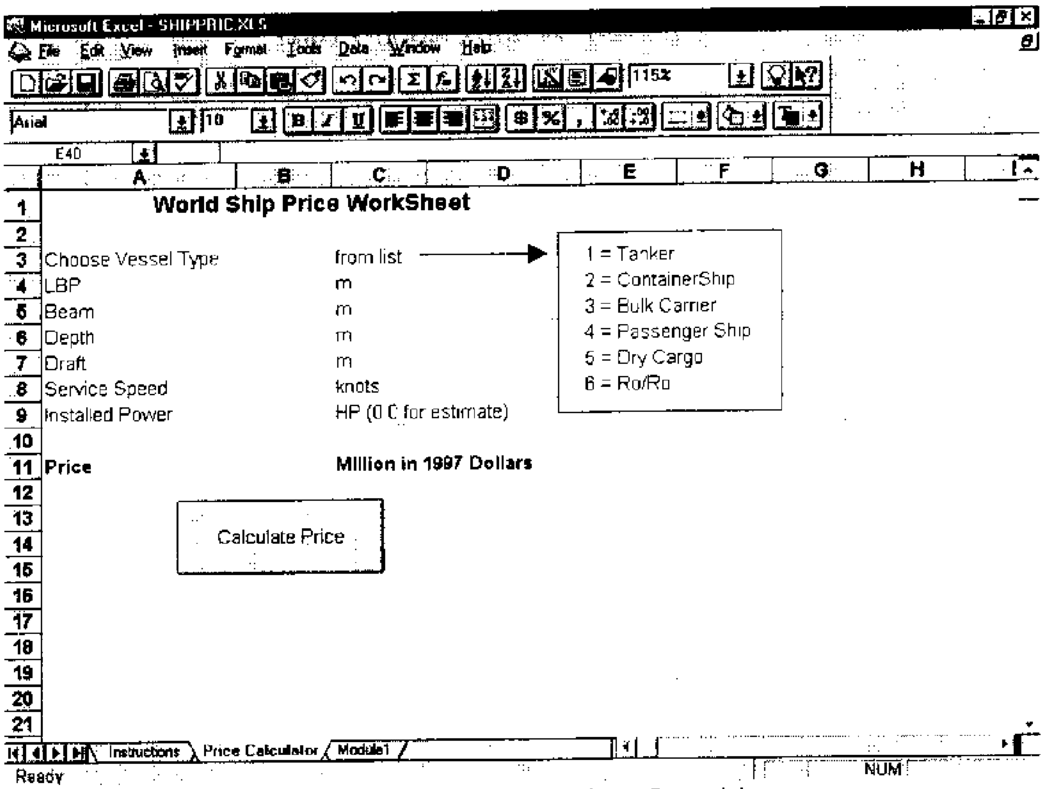

Figure 4 – World Price Predictor Spreadsheet

Conclusion

The Portfolio of World Class Ship Designs program for the GCRMTC provides a number of market worthy commercial ship designs at the preliminary design level for use by shipyards as baseline designs. Currently the designs for tankships and containerships have been completed, and the design for Fast Monohull RO/RO Passenger Ferries and Coastal Patrol Craft are under development. Shipyards can select and develop standardized designs to the contract level for those designs that are consistent with their long-range marketing strategy. The portfolio program has also provided the opportunity to develop an early stage design computer synthesis modeling and cost estimating suite of software. These computer programs are based on an approach utilizing user supplied databases and design parameters which improves the reliability of the results over that of a purely parametric approach. The portfolio design and cost estimating synthesis tools are structured for use in trade-off studies and to evaluate the impact of owner specified variations from shipyard standard design requirements. The structural portion of the production program and cost estimating modules are complete and are being expanded to include mechanical systems and outfitting. These early stage design tools can assist shipyards in responding rapidly and confidently to client inquiries for shipbuilding projects.

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THE USE OF OBJECT ORIENTED MODELLING IN THROUGH LIFE COSTING OF SHIPBOARD SYSTEMS

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Introduction

In marine technology, as in other branches of engineering, there has been a tendency towards greater integration of client and contractor interests. Contract mechanisms such as EPIC (Engineer, Procure, Install, Commission) and alliancing allow the designer and builder to become involved with the operator in the through life performance of made-to-order (MTO) products, e.g. in the offshore industry and in military procurement. The emphasis is moving away from satisfying the performance specification at minimum capital cost with little or no consideration of whole life effects, to allowing Through Life Costing (TLC) considerations to influence the design. Changes in performance with time, reliability and maintainability considerations, and end-of-life disposal may well influence the choice of the design solution selected.

Since much of the capital cost as well as the basic performance capability of a large MTO product is largely determined during the early design phases, e.g. feasibility when major equipment will be sized and selected, it is important that a number of alternatives are investigated before design decisions are committed.

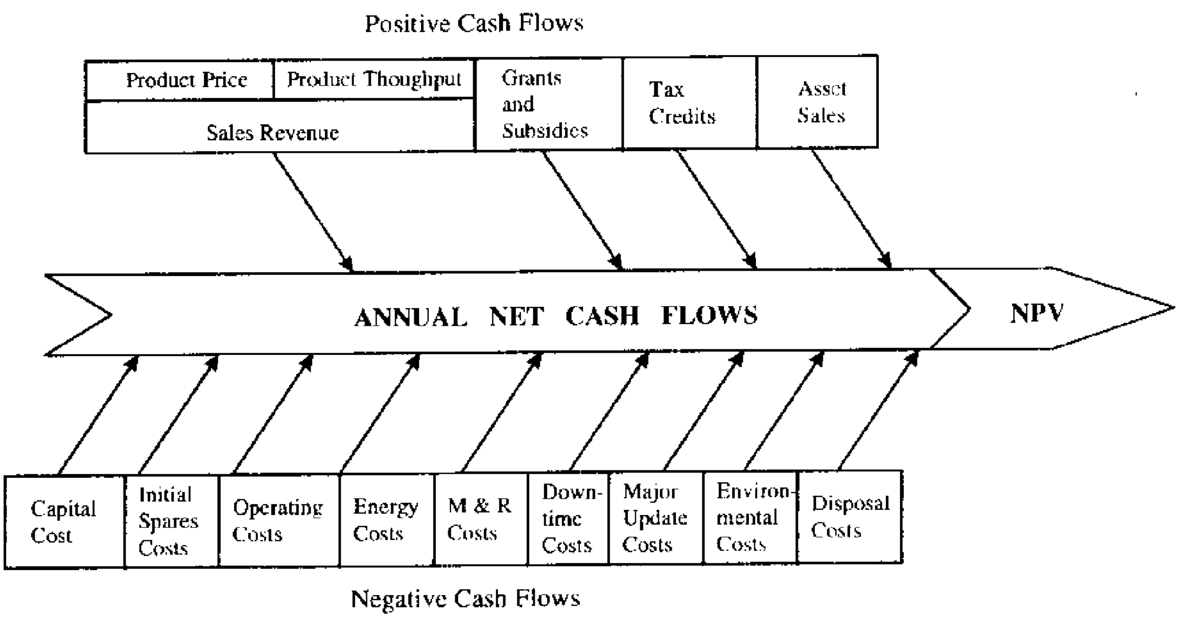
TLC employs well established discounted cash flow techniques normally used for investment appraisal, whereby estimates of income and expenditure (both Capex and Opex) are made over the life of the project. These are discounted at some interest rate reflecting the rate of return expected from the project, to give a figure for Net Present Value (NPV) (Ref. 1) can be considered as the lifetime value of the project, equivalent to an instantaneous capital gain of that amount, hence negative values imply inadequate rate of return. Since most MTO products produce an income, e.g. oil production or freight revenue, then benefits can also be incorporated. Hence TLC is one means of undertaking a Cost-Benefit Analysis, even though this term is often applied in a safety context.

Spreadsheets are widely used in such evaluations, manually fed with data by project managers and finance personnel. But what is desirable in TLC are links between the design definition, the TLC procedures, and the incorporation of the many phases of the life cycle (some of which may be ignored, e.g. midlife upgrading or disposal) as well as the recognition that performance is unlikely to remain constant over the life. It is also desirable to link any TLC system with sources of data, which may range from suppliers' catalogue type data of equipment properties, to reliability models of major components or sub-systems.

Models should also be applicable at different levels of complexity, reflecting the relatively long design period of most MTO products, during which more information becomes available. If one includes definition for production as 'design', as well as concept and embodiment, that period may extend to several years. What is required is a flexible model which can be added to as the design definition increases, and as more data becomes available built up from industry/company specific databases, e.g. on equipment supplied by a sub-contractor for a ship.

Object oriented modelling lends itself to such concepts, whereby objects which define the system or components can be added to represent lower levels in sub-systems, e.g. auxiliary systems → electrical power generation → diesel generator set → alternator. TLC then becomes feasible at an appropriate stage of design, e.g. when comparing different numbers and capacities of generators (see later example).

Research at the Newcastle Engineering Design Centre (EDC) for a wide variety of industries (shipbuilding, offshore oil production, process plant, power generation etc.) has shown that there are generic similarities between such products and their procurement. MTO products are largely assemblies of bought-in equipment, supporting structures and connectives like piping and cabling. With life cycles of the order of 30 years, often with the same operator, TLC issues become important, especially as capital cost typically represents only around one-quarter of (discounted) through life costs. Over that period there will be changes in performance capability, in market demands and prices of output, and in regulatory requirements, e.g. environmental legislation.



Company Cash Flow Model

Figure 1

A project has been undertaken in the EDC to demonstrate that a generic TLC object oriented model could be developed, which would allow the designer to compare alternatives earlier in the design process, taking account of more factors than usual. Figure 1 shows the generic elements, which are the main cost and performance drivers. They are capable of being adapted to different MTO product structures and technical and economic data. For example 'environmental costs' may be associated with diesel engine emissions in a ship, but with waste disposal in a chemical plant. Each element is essentially determined from relevant sections of the database from typically:

Cost = Quantity x Unit cost rate

which may well vary at different stages of the life profile, e.g. fuel consumption increasing with age. The example presented in this paper compares a shipboard system consisting of different numbers and capacities of diesel generators.

Developing A Through Life Costing Software Tool

The development of a design involves hundreds or even many thousands of sequential decisions as the process moves from concept through to the embodiment or detail stage. The scope of the initial decisions is broader with a much greater influence on the final design and, therefore, they have the greatest effect on the final economic performance. It is usual practice for estimates of the initial costs and through life revenues and operating costs to be determined by different people in different departments from those developing the product. Often producing such estimates is time consuming and is only attempted towards the completion of the design. This approach does not make it possible for many of the design decisions to be based on economic assessments.

There is a clear requirement for the cost and revenue information relevant to the current state of the design to be available to the designer. Such information would make it possible for decision making to be governed by economic considerations. It is important to note that the need is for reliable *comparative* information and, therefore, high absolute accuracy is not essential. This information can be provided if cost and performance data is associated with each component through a 'driver' which takes into account its performance parameters, such as weight or power. Work at the Newcastle EDC has demonstrated the feasibility of achieving this objective with computer assistance by producing and testing prototype software representing a shipboard system.

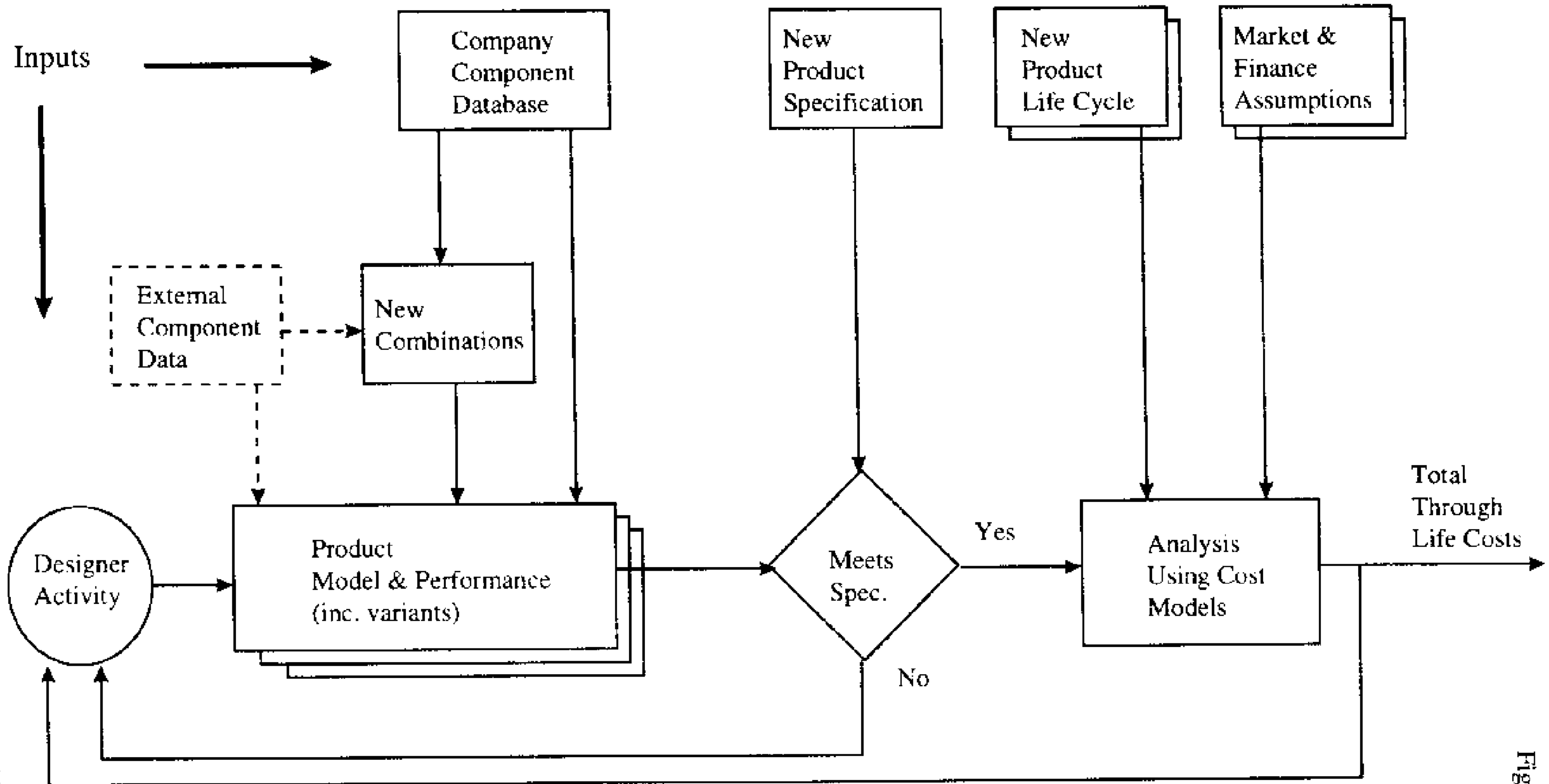
An important requirement is for a company archive of previous products, and more particularly, the data on the main components from which they were assembled. The 'reuse' of this company knowledge is essential for the cost effective use of any such system.

The system is designed to be:
- Intuitive
- Flexible
- Complementary to normal design activities
- Capable of accessing performance and cost databases

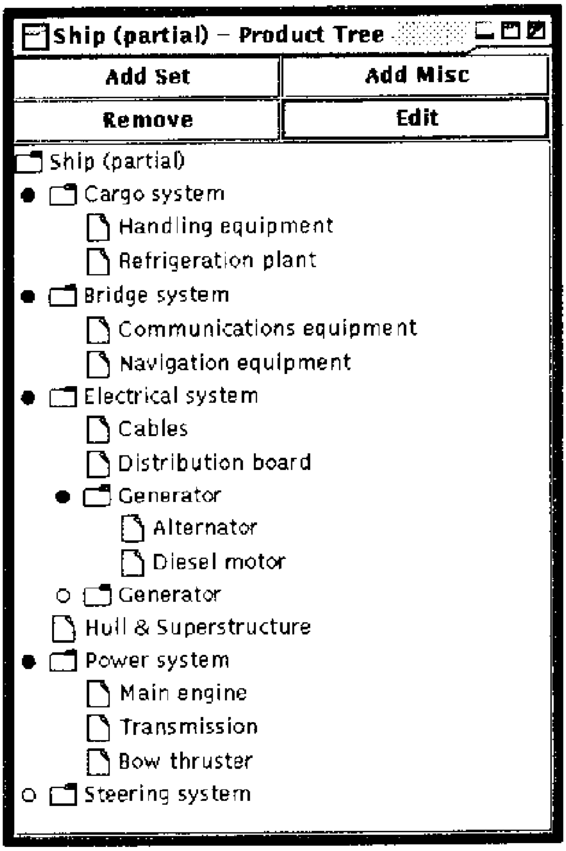
The last requirement should alter the focus of departments, such as Costing, to provide data in an accessible form but this is essential if the benefits of cost based design are to be achieved. Operating in this way brings the application of current company costs and cost rates, not to mention future estimates, into the design process. Figure 2 shows the basic operation of the cost/revenue based design process from the designer's perspective.

The designer progressively refines the design of the product by building and changing the 'Product Model' which has a hierarchical inverted tree structure. We use the term 'product model' to mean the general object/component structure, rather than primarily the geometrical definition. A typical product model developed with the TLC software is shown in Figure 3.

Figure 2



The Through Life Cost Based Design Process



Typical TLC Product Model Figure 3

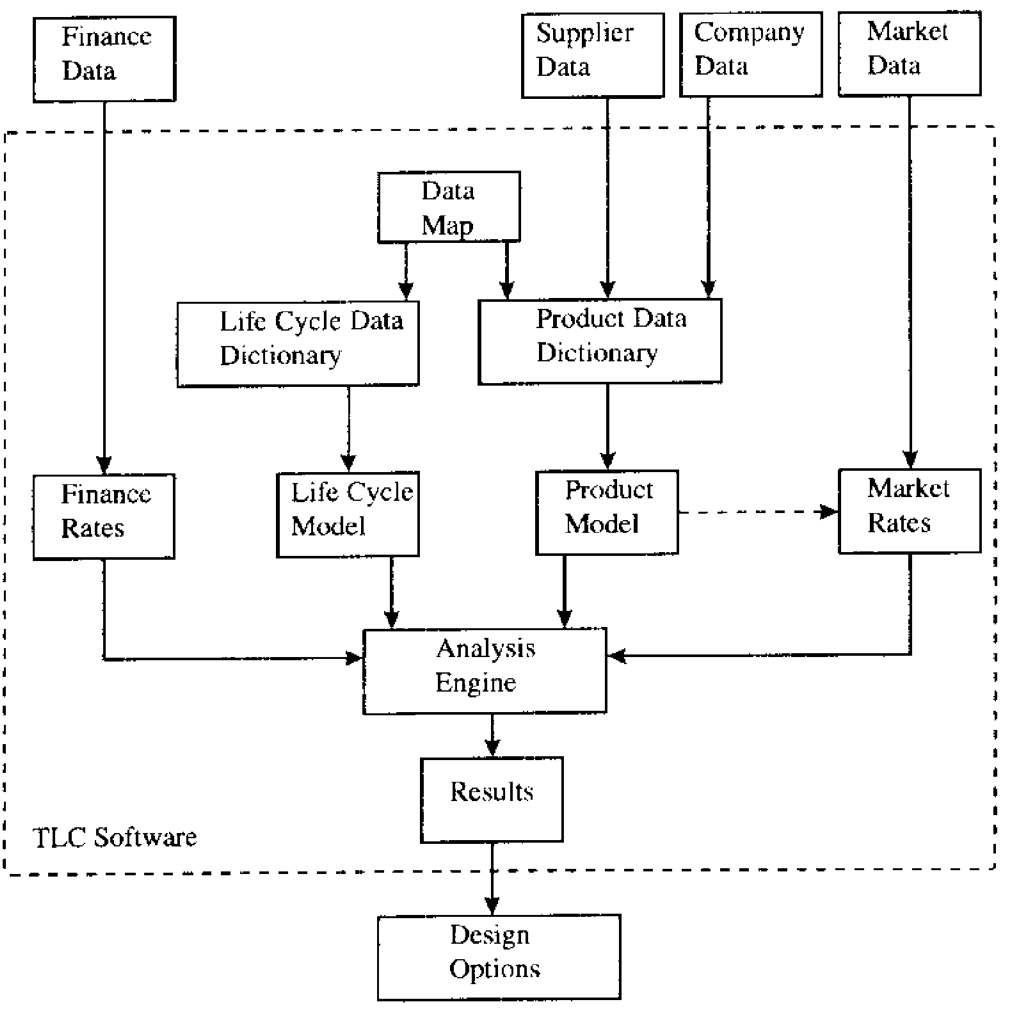
Component information should be retrievable from equipment suppliers as well as from company databases. At any time the stage of development can be checked for compliance with the requirements of the Product Specification. Failure obviously implies the need for revision of the design. Any design which satisfies these requirements can then be subjected to a full through life economic assessment using an assumed life cycle profile and projected market and other financial forecasts. An optimisation process requires the comparison of the figures for the current model with those for previous models. A valid preference will result provided the comparative figures are consistent. The robustness of the design philosophy can be checked by determining the economics with varied life cycles and operating conditions.

Experience in producing the software demonstrated that an Object Oriented (OO) approach both for programming and object storage enabled the prototype to be rapidly developed. Modern OO CASE tools would also be used in any future projects. The flexibility requirement can be met by using text based 'dictionaries' which describe the components and pull in the necessary analysis and driver objects to take account of differing component parameters and sub-component combinations. A similar approach is used for the Product Specification, the Product Life Cycle definition and the Financial assumptions. In many cases options are possible and the system must store and recall the specific combination required for each analysis.

Data Structures To Support TLC Model Development

The prototype TLC software developed by the EDC is more sophisticated in its method of operation than the typical spreadsheet based systems currently used. During its development the research team decided to code the software in Java, so that software would not be dependent on any particular operating system, thereby allowing it to be used with virtually any computer.

Standard Object Oriented Modelling (OOM) system analysis techniques were utilised to enable the coding requirement to be defined before programming actually began. Storyboarding and other graphical modeling techniques enabled a detailed picture of what was required within the TLC tool to be defined, which in turn enabled the required OOM classes to be defined from which the coding base was developed. The main parts of the software and their relationship to each other are shown in Figure 4.



TLC Software Information Flow

Figure 4

The TLC software requires that a database is established before specific models can be created by designers. This comprises three data stores: the 'data map', the 'product data dictionary' and the 'life cycle data dictionary'.

The 'data map' is a user-defined list of Features, Properties or Characteristics (FPCs) that can be attributed to an assembly or component of a product. Each data map entry is composed of three elements:

1. Name, i.e. the name of the FPC, e.g. fuel oil, electrical power.
2. What type of data is associated with the FPC, e.g. float, integer.
3. The units that the data is specified in, e.g. litres, kW

The *product data dictionary* is a user-defined list of components, sub-assemblies, assemblies and systems, from which the products that are to be modelled are selected. Each item contains details of the FPCs that are relevant to it. To allow for the greatest amount of flexibility and ease of use, it is envisaged that industry sectors and individual companies would create specific data dictionaries.

When a data dictionary item is created, the user must decide if the item produces a 'benefit' (such as a saleable manufactured product) and which of the primary cost areas are appropriate to the item from the following list:

1. Capital or Procurement Costs
2. Initial Spares Costs
3. Repair cost
4. Maintenance costs
5. Consumable costs
6. Environmental costs
7. Manning costs
8. Update costs
9. Survey (regular major overhaul) costs
10. Decommissioning costs
11. Total cost

In use, the *product data dictionary* provides the user with a menu of items from which to select when building a model. This ability to select the items that are required and to vary the configuration in which the items are placed, allows the user to explore the comparative through life costs of various concept design options. While the tool is primarily aimed at use during concept design, there is no reason why a user should not model an already existing design, if this was required. Such an exercise could be used for providing a baseline indication of the through life costs of the design concepts under consideration, or the impact of anticipated changes in, for example, environmental legislation over the projected remaining life.

The *life cycle data dictionary* follows the same format that of the product data dictionary. The purpose of this data dictionary is to provide 'building blocks' that can be used to construct the various phases of a product's life, from procurement to decommissioning, including the ability to construct complex operational cycles, e.g. ship voyages.

Model Building From Marine Systems Data

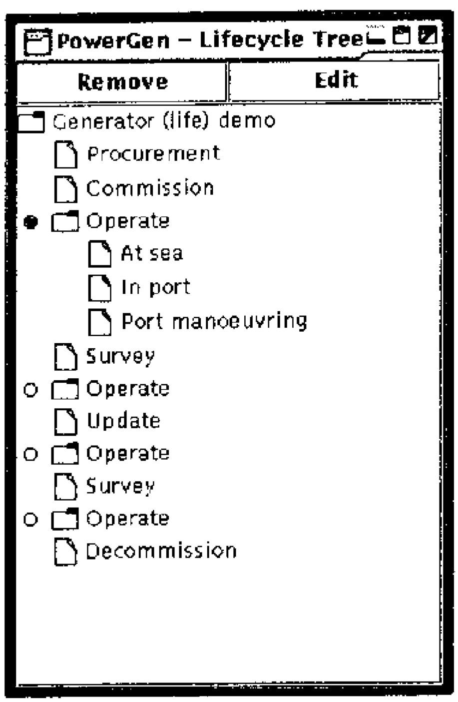
A primary philosophy of the research team was to ensure that the software that was developed would be comfortable for the design engineer to use. Therefore, a prime consideration was to use a familiar engineering vocabulary. This is particularly so with the FPCs of the data map and the items contained in the data dictionary.

An important part of developing the TLC tool involved creating a syntax to be used when building a model, together with a set of model making rules. The syntax and rules are important in ensuring the working models function logically. The software has a checking system that validates a model before the analysis engine performs an analysis calculation, to ensure that all the information needed is available.

The TLC tool software has been written so that it is possible to have several concept designs under development and evaluation at any one time. This requires, that for each design, performance parameters are established, e.g. payload, speed, fuel consumption.

There are four stages in creating a model, assuming that the preparatory work of creating a data map and a data dictionary has been carried out. They are: product model creation, life cycle model creation, adding market data and adding financial data. Each of the four stages has an important role in the TLC analysis, therefore, only when all four stages have been carried out can the model be validated and a TLC analysis carried out.

The product model is a hierarchical decomposition of the item that is being modelled. The level of decomposition is a user's choice and can be as shallow or as deep as required. When the software is used at the concept design stage, the product model will be at a reasonably high level, most likely major assembly level. The software is also capable of producing a detailed product model down to component level, if required. Furthermore, the software does not need to model a complete product, decisions can be made at the sub-system level, e.g. the genset example described later.



Typical Life Cycle Model Figure 5

The life cycle model is a linear, time-wise, representation of the life cycle that the user wants the product model to follow. It is created using life cycle event components that have been pre-defined in a appropriate life cycle data dictionary. While the overall life cycle will be from birth to death, the software allows for cyclic events within a given time frame to be accommodated, e.g. ship voyages. A screenshot of a typical life cycle model developed with the TLC software is shown in Figure 5.

Market data is added to the model relevant to the product model being evaluated. Market data items are those for which there is a market price, e.g. freight rates, wage rates, fuel price.

The financial data that is required is pre-defined by the software, largely in the form of discount rate and cost escalation rates (Ref. 2).

A TLC Comparison Of Shipboard Generator Alternatives

The TLC software is generic and can be used to model through life costs of a range of engineered products. The example below is a relatively simple one to demonstrate the capability of what is a sophisticated piece of software. The comparison of various options for the provision of shipboard electrical power generators form the basis of the example. The total auxiliary power requirements can be met by different combinations of number and capacity of diesel gensets, from a typical manufacturer's standard range. Two types of generator are selected in four different configurations. These are:

1. Four 44kW generators, total power available 176kW
2. Five 44kW generators, total power available 220kW
3. Two 80kW generators, total power available 160kW
4. Three 80kW generators, total power available 240kW

The generators were required to provide duty cycles as follows: at sea 44kW, port manoeuvring 150kW, in port 80 kW. All the generator combinations could easily handle the maximum load of 150kW, but only two of the options could handle the maximum load requirements with one generator out of action. A generator manufacturer's specification sheets were used to provide the majority of the technical data required to carry out the TLC estimation, while the economic data was typical of marine applications.

The TLC calculations are based on the following life cycle for the ship: three year procurement phase, three months commissioning; 28 years operating phase based on: at sea, port manoeuvring, in port cycle, surveys after 7 and 21 years of operations, modernisation after 14 years of operation; one year for decommissioning at the end of life. Within the operating phase the effect of equipment failure and maintenance are taken into account when availability and repair costs are calculated.

When a life cycle cost estimation is performed for each of the above genset combinations, using identical life cycle, market and financial data, a set of results are produced that can be used to make a comparison of the various alternatives. The software allows the user to investigate the various costs attributed to the design, e.g. both yearly cost and total costs. Table 1 shows the whole life costs for the scenario described above.

Since all the alternatives meet the same auxiliary power demands, the benefits are identical. If required, a 'value' could be placed on the output in terms of £/kWh, but this would not change the ranking in this example.

It can be seen in the results in Table 1 that in present value terms that two 80kW generators are the least expensive to run over a 28 year operational life. This example also demonstrates the necessity of using Net Present Value (NPV) when evaluating benefits/cost over an extended period of time. This is shown by the fact that the 4x44kW and the 3x80kW generators are ranked second and third respectively when NPV is used but these positions are reversed if the undiscounted total is used. It should be remembered that factors other than cost may have to be taken into consideration when making a decision. In this example, the redundancy necessary to have a generator available to come on line if an operational generator should fail, rather than await repair, may be highly valued. If this was the case, the two 80kW and four 44kW options would be less attractive.

Table 1: Genset comparison where manning costs are high and supervision time varies

Lifetime Costs £	4 x 44kW	5 x 44kW	2 x 80kW	3 x 80kW
Capital	176000	220000	160000	240000
Initial spares	16000	20000	16000	24000
Repair	120000	120000	184000	180000
Maintenance	61600	61000	72300	72000
Consumables (fuel)	514426	511335	508794	506877
Manning for generators	746950	931751	373356	559009
Update	50000	62500	40000	60000
Survey	2000	2500	1200	1800
Decommission	10000	12500	5000	7500
Total over 32 years (undiscounted)	1696977	1941587	1360650	1651187
Total discounted at 10% (Net Present Value)	515163	601139	425964	545095
Rank order	2nd	4th	1st	3rd

The software allows the users to test various scenarios. In the example above the manning cost was proportional to the number of generators and the cost of manning was set at £15 per man hour. In a changed scenario, it is assumed that a similar amount of time is needed to supervise the generators in each of the options regardless of whether two, three, four or five generators are used, while the manning costs are lowered to £12 per man hour due to employing lower cost labour. Then the results in Table 2 obtained.

Table 2: Genset comparison where supervision time is low and supervision time is constant

Lifetime Costs £	4 x 44kW	5 x 44kW	2 x 80kW	3 x 80kW
Capital	176000	220000	160000	240000
Initial spares	16000	20000	16000	24000
Repair	120000	120000	184000	180000
Maintenance	61600	61000	72300	72000
Consumables (fuel)	514426	511335	508794	506877
Manning for generators	446676	447240	448027	447207
Update	50000	62500	40000	60000
Survey	2000	2500	1200	1800
Decommission	10000	12500	5000	7499
Total over 32 years (undiscounted)	1396703	1457076	1435322	1539385
Total discounted at 10% (Net Present Value)	441673	482361	444234	517685
Rank order	1st	3rd	2nd	4th

As can be seen above the ranking of the generators based on present value has now changed. In addition, by varying a cost factor that has a significant effect on total cost, in this case manning, the total cost gap between the various option has been narrowed. In this example, two other cost factors are significant namely: capital cost and consumable costs. Varying either of these even by a relatively small amount could have a similar effect on the overall TLC of this example.

Figures 6 and 7 are an example of screenshots for case 1 of Table 2, showing how the various through life costs, both undiscounted and discounted are made up.

From this example it can be seen that exploring various TLC scenarios for a particular design can provide the designer with valuable insight in comparing alternatives and on which to base design decisions.

Conclusions

As through life considerations continue to grow in importance, the need for designers to take them into account explicitly when developing a design increases. No longer can they design and build a product only considering procurement cost, but now must consider the costs that affect a product throughout its life. Companies that can offer designs with more favourable TLC's are more likely to obtain a significant advantage in the market place. As the pressure of the world market place increases so making the trade more competitive, customers not only want a high standard of service, but that it is also at the lowest TLC. The way to ensure that the demands of modern day trade are met is by ensuring that the implications are taken into account at the concept design stage, since it is reckoned that 80% of products TLC's are committed at this stage (Ref. 3).

The prototype software that has been developed shows that it is possible to develop a generic TLC tool. The approach that has been developed can just as easily model a ship's TLC as an oil rig or a process plant.

The research to date has concentrated on proving the concept. The next stage is to develop the model further, so that it can access more external information, e.g. reliability studies and supplier data, and to incorporate them with risk analysis (both financial and market) and sustainability issues.

Acknowledgement

The authors wish to acknowledgement the work of Richard Bull (formerly of the Newcastle EDC), Rich Soft Ltd, Newcastle, UK, who was responsible for the coding of the TLC software described in this paper.

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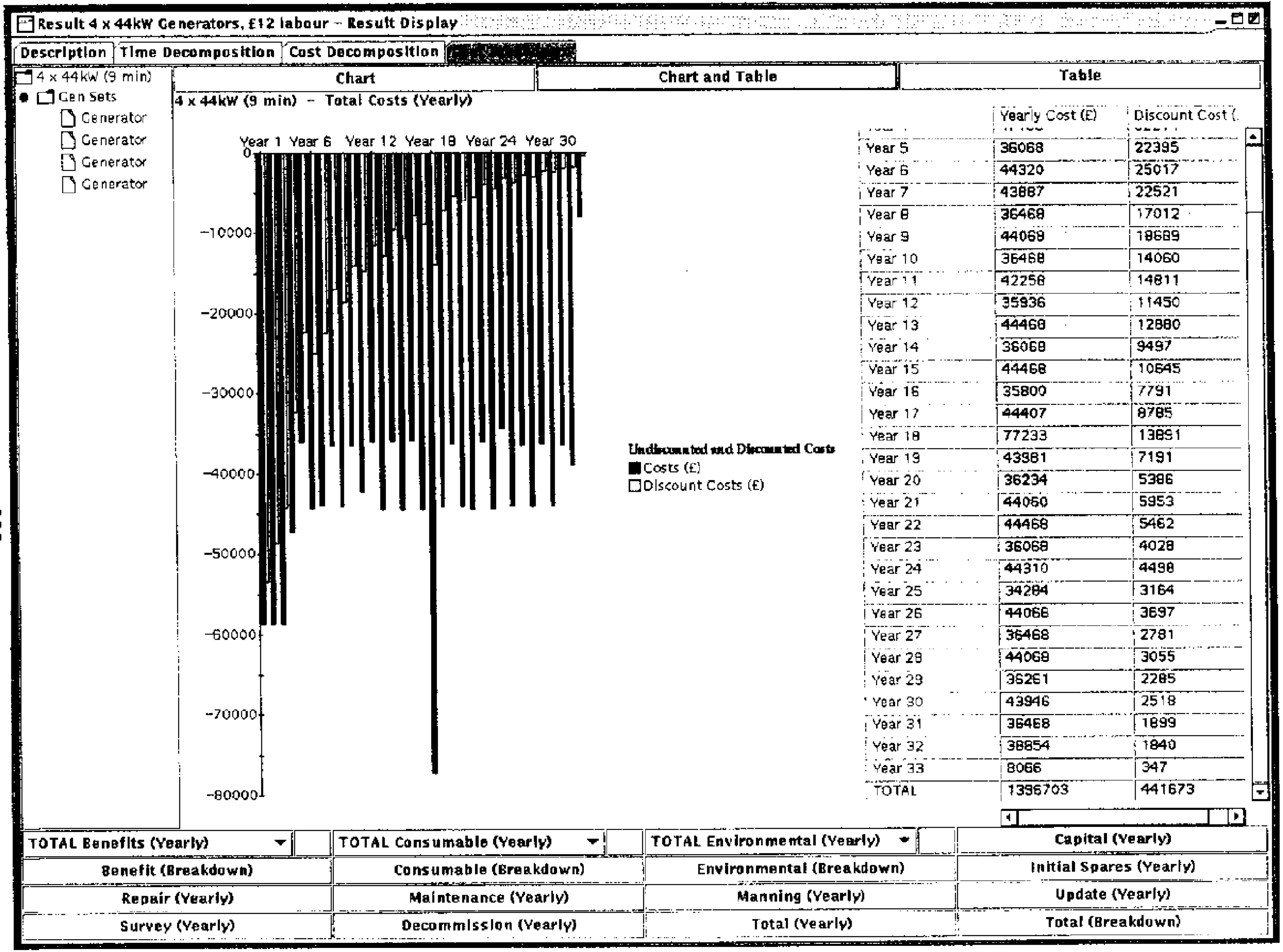
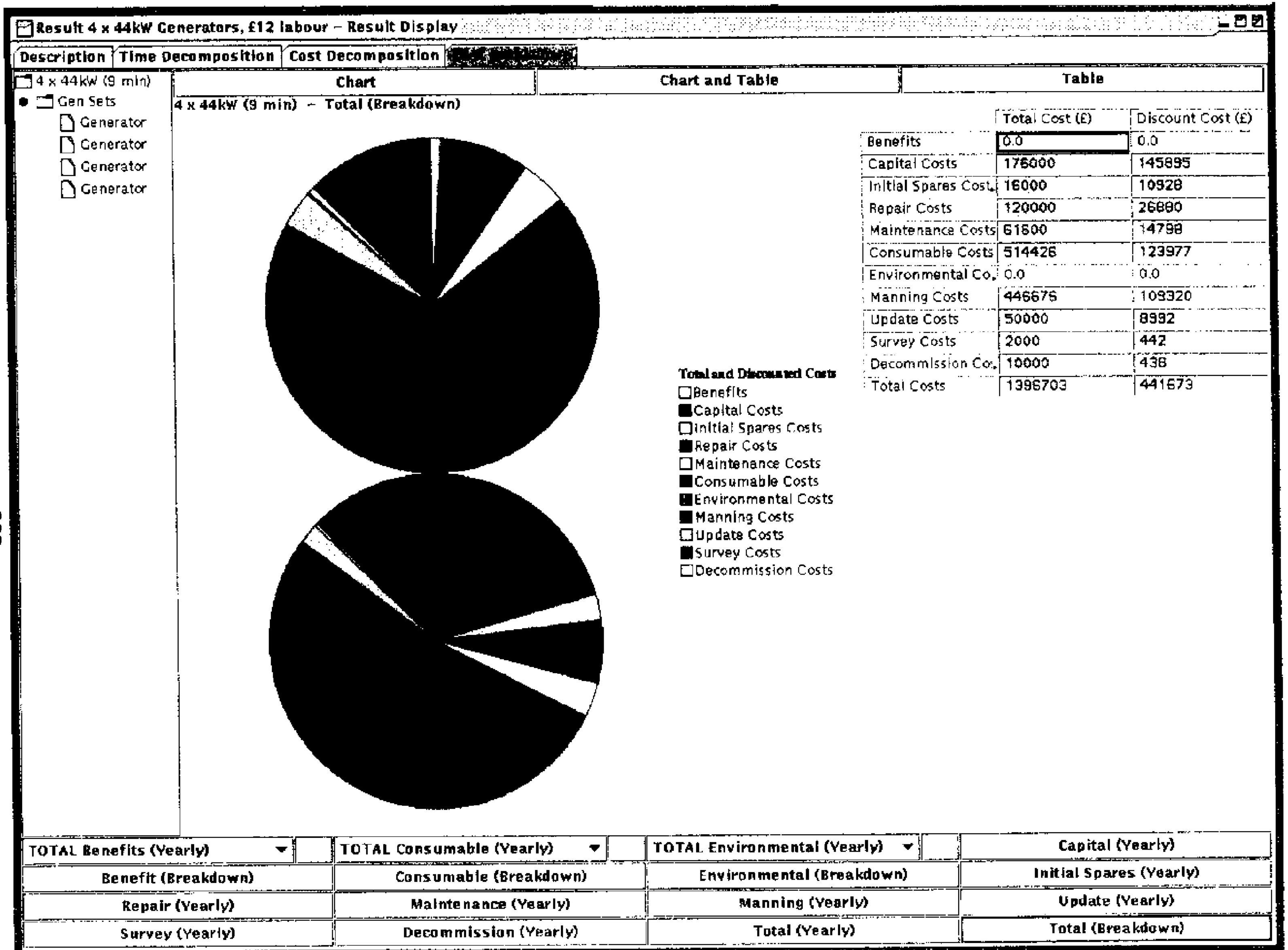


	Yearly Cost (£)	Discount Cost (
Year 5	36068	22395
Year 6	44320	25017
Year 7	43887	22521
Year 8	36468	17012
Year 9	44069	18689
Year 10	36468	14060
Year 11	42258	14811
Year 12	35936	11450
Year 13	44468	12880
Year 14	36068	9497
Year 15	44468	10645
Year 16	35800	7791
Year 17	44407	8785
Year 18	77233	13891
Year 19	43981	7191
Year 20	36234	5386
Year 21	44060	5953
Year 22	44468	5462
Year 23	36068	4028
Year 24	44310	4498
Year 25	34284	3164
Year 26	44068	3697
Year 27	36468	2781
Year 28	44068	3055
Year 29	36261	2285
Year 30	43946	2518
Year 31	36468	1899
Year 32	38854	1840
Year 33	8066	347
TOTAL	1396703	441673

Typical Screenshot of TLC Software Tool

Figure 6



Typical Screenshot of TLC Software Tool

Figure 7

SAFEHULL FEM FATIGUE ASSESSMENT OF SHIP STRUCTURAL DETAILS

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Introduction

Fatigue is responsible for a large proportion of cracks occurring in welded ship structural details. For many years fatigue related failure has become a major concern in the maintenance of existing vessels and the design of new vessels. As reported in [1], numerous cracks were experienced by relatively new oil carriers constructed of higher-strength materials. As indicated, more than 10 fatigue cracks per damaged ship were found during damage surveys of 48 "second generation" VLCCs using HT32 and HT36 steels. The cracks were discovered when the ships were, on average, only 3 to 4 years old without any significant corrosion or wastage. The cracks occurred mostly on the side longitudinals at the connections to transverse bulkheads or transverse webs. Fatigue cracks were also reported on other types of vessels. For example, in some bulk carriers, cracks were commonly found in the "hard" corners of the lower hopper tanks connecting to the side frames, and the lower stools connecting to the double bottom.

It is important to note that the fatigue strength of welded structural details (with stress concentration) is not dependent on the tensile strength of the steel. Fatigue refers to the failure of materials under repeated actions of stress fluctuation. The loads responsible for fatigue are generally not large enough to cause material yielding. Instead, failure occurs after a certain number of load or stress fluctuations. Two distinct features, typical of high-cycle fatigue, are generally seen on the cracked surfaces of fatigue failure of ship structures: 1) the material has undergone only minor yielding, and the strain was essentially elastic, and 2) the fracture surface is smooth, with characteristic chevron lines reflecting the variable intensity of loading of low and high sea states during the vessel's service life.

The American Bureau of Shipping (ABS) has over the years devoted considerable effort in the development of the SafeHull system to cope with the assessment of yielding, ultimate strength and fatigue of hull structures. ABS SafeHull is a dynamic based design and analysis tool. To provide a practical tool for fatigue strength assessment, the SafeHull approach is based on the so-called "*Simplified Fatigue Analysis*" with the assumption that the long-term stress histogram of the hull structure follows the Weibull probability distribution. In the paper, the SafeHull fatigue assessment procedures, implementations and illustrations are presented.

Fatigue Assessment Procedure

Simplified Fatigue Analysis

To evaluate the fatigue life of a hull structure, two basic sets of information are invariably required, namely, the material characteristics cast in the form of S-N curves and the long-term stress distribution (or stress histogram) of the structure. Both sets of information should be determined in a satisfactory manner. For stress histograms, it is necessary to account for all stress variations during the life of the ship, with due consideration given to its loading conditions, speed, wave environments, motion response, and resulting loads and structural response. Depending on how the long-term stress distribution is determined, the analysis procedure for fatigue assessment of hull structures can be defined as the so-called "*spectral fatigue analysis*" or as the so-called "*simplified fatigue analysis*" described in the following.

The ***SafeHull*** approach is based on the "*simplified fatigue analysis*" with the assumption that the long-term stress histogram of the hull structure follows the Weibull probability distribution. It has been known that a vessel's long-term stress distribution resulting from random sea loading can be fit closely into the two-parameter Weibull probability distribution. Based on the assumption, fatigue damage (or fatigue life) can be obtained in a closed form as expressed in the following equation [2]:

$$D = \frac{N_L}{K} \frac{S_R^m}{(\ln N_R)^{m/\xi}} \mu \Gamma\left(1 + \frac{m}{\xi}\right) \tag{1}$$

(*Fatigue life = Design Life / D*)

where $\mu = 1 - \left\{\gamma\left(1 + \frac{m}{\xi}, \nu\right) - \nu^{-\Delta m/\xi} \gamma\left(1 + \frac{m + \Delta m}{\xi}, \nu\right)\right\} \Big/ \Gamma\left(1 + \frac{m}{\xi}\right)$

ν = $(S_q / S_R)^{\xi} \ln N_R$

N_L = $f T$, total number of cycles in life time

N_R = Number of cycles corresponding to the probability of exceedance $1/N_R$

S_R = Most probable extreme stress range in N_R cycles (i.e., at the probability of exceedance of $1/N_R$)

D = Cumulative fatigue damage ratio

f = Life time average of the response zero-crossing frequency (Hz)

T = Base time period, taken as the design life of the structure (seconds)

ξ = Weibull shape parameter of stress range

S_q = S-N stress range at the intersection of two segments

m, K = Parameters of the upper segment of the S-N curve

Δm = Slope change of the upper to lower segment of the S-N curve

$\gamma(a,x)$ = Incomplete gamma function, Legendre form

$\Gamma(a)$ = Gamma function.

As can be seen in Equation (1), the two parameters of the Weibull distribution used are the stress range S_R at the probability of exceedance of $1/N_R$, and the *Weibull shape parameter* ξ. For a given set of S_R, ξ and *S-N* curve, the fatigue damage (or fatigue life) can be readily obtained using the equation. Similarly, for a given set of ξ, *S-N* curve and a specified fatigue damage (or fatigue life), the stress range S_R can be determined.

The SafeHull assessment procedures were developed from various sources including the Palmgren-Miner linear damage model, U. K. DEn's S-N curves, environment data of the North-Atlantic Ocean, etc. In assessing the adequacy of the structural configuration and the initially selected scantlings, the fatigue strength of the hull girder and individual structural members or details is to be in compliance with the failure criteria specified. The SafeHull fatigue criteria were established to allow consideration of a broad variation of structural details and arrangements so that most of the important structural details in the vessel can be assessed for their adequacy in fatigue strength. To this end, the structural response should be calculated by a finite element structural analysis as defined here or by other equivalent and effective means. Due consideration should be given to structural members or details expected to have high stresses. While this is a simplified analysis, some judgments are still required in applying the approach to the actual design.

Weibull Shape Parameter

To apply the *simplified fatigue analysis* described in the guidance, one of the two parameters of the Weibull distribution required is the long term stress distribution parameter or the *Weibull shape parameter* γ (i.e., ξ in equation 1). The fatigue damage is directly represented by the numerical value of this parameter, a higher value indicates a higher fatigue damage. The Weibull shape parameter typically varies between 0.8 to 1.1, depending on the dominant period of the hull structural response and the considered wave environments.

Based on the results of numerous case studies, ABS provides in the "*Guide for Fatigue Strength Assessment of Tankers*" [3] the following empirical formulas for estimating the Weibull shape parameters for structures at various locations in ship:

$$\begin{aligned}\gamma &= 1.40 - 0.036\,\alpha\ L^{1/2} && \text{for } 190 < L \leq 305 \text{ m} \\ &= 1.54 - 0.044\,\alpha^{0.8} L^{1/2} && \text{for } L > 305 \text{ m}\end{aligned} \tag{2a}$$

$$\begin{aligned}\gamma &= 1.40 - 0.020\,\alpha\ L^{1/2} && \text{for } 623 < L \leq 1000 \text{ ft} \\ &= 1.54 - 0.024\,\alpha^{0.8} L^{1/2} && \text{for } L > 1000 \text{ ft}\end{aligned} \tag{2b}$$

where α = 1.0 for deck structures, including side shell and longitudinal bulkhead structures within $0.1D$ from the deck.

= 0.93 for bottom structures, including inner bottom, and side shell and longitudinal bulkhead structures within $0.1D$ from the bottom.

= 0.86 for side shell and longitudinal bulkhead structures within the region between $0.25D$ from deck and $0.2D$ from bottom.

= 0.80 for transverse frame and transverse bulkhead structures, including vertical webs and horizontal girders.

L and D are the ship length and depth, as defined in the ABS Rules [4].

Also, α may be linearly interpolated for side shell and longitudinal bulkhead structures between 0.10D and 0.25D from the deck, and between 0.10D and 0.20D from the bottom.

Basic Design S-N Curves

The S-N curves used in the SafeHull fatigue assessment criteria are the "*Basic Design S-N Curves for Non-nodal Joints*", given in the "*Offshore Installations: Guidance on Design, Construction and Certification*", issued by the Department of Energy (DEn) of the United Kingdom (now HSE, Health and Safety Executive) [5]. The basic design S-N curves were established based on extensive experimental and theoretical data on the fatigue performance of welded tubular and plate connections accrued as a result of the DEn's *United Kingdom Offshore Steels Research Project*. These data apply to structural steels having yielding stresses lower than 400 N/mm^2.

The DEn's *Basic Design S-N Curves* are shown in Figure 1, as identified by eight curves, B, C, D, E, F, F2, G, and W. Each curve represents a class of welded details, categorizing mainly by the following:

i) the geometrical arrangement of the detail,
ii) the direction of the fluctuating stress relative to the detail,
iii) the method of fabrication and inspection of the detail.

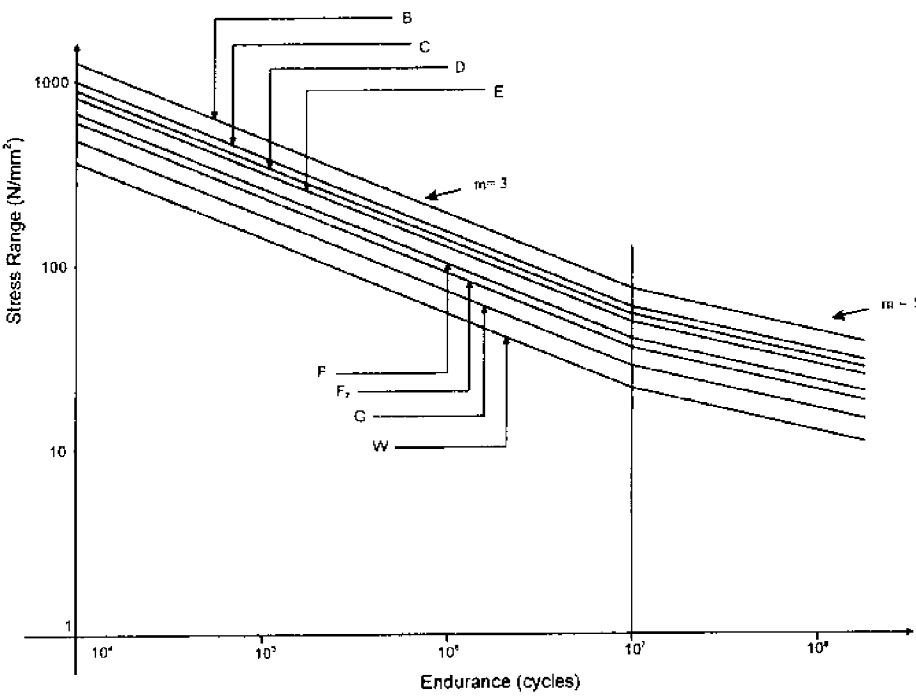


Figure 1. U. K. DEn Basic Design S-N Curves

The basic design S-N curves were defined based on statistical analyses of relevant experimental data, and were taken to represent two standard deviations below the mean lines. Their use therefore implies a finite probability of failure at the calculated life. For areas of reduced structural redundancy, areas that are very difficult to inspect, or for critical structural members, an additional factor on life may need to be considered.

The *DEn S-N curves*, as can be seen in Figure 1, consist of two segments each, with a linear relationship between *log (S)* and *log (N)*, and can be expressed in the following form:

$$log\,(N) = log\,(K) - m\,log\,(S) \tag{3a}$$

or

$$N = K\,S^{-m} \tag{3b}$$

where $log(K) = log(K_1) - 2\sigma$

- S is the stress range of stress fluctuation, between a peak and the subsequent valley,
- N is the number of cycles to failure under stress range S,
- K_1 is a constant relating to the mean S-N curve,
- σ is the standard deviation of $log\ N$,
- m is the inverse slope of the S-N curve.

All eight curves change slope at N equal to 10^7 cycles. The relevant values of the various terms in the above equation for both segments are given below:

Class	------- $N \le 10^7$ -------		------- $N \ge 10^7$ -------		Std. Dev.
	m	K	m	K	σ
B	4.0	$1.013\text{x}10^{15}$	6.0	$1.013\text{x}10^{17}$	0.1821
C	3.5	$4.227\text{x}10^{13}$	5.5	$2.926\text{x}10^{16}$	0.2041
D	3.0	$1.519\text{x}10^{12}$	5.0	$4.239\text{x}10^{15}$	0.2095
E	3.0	$1.035\text{x}10^{12}$	5.0	$2.300\text{x}10^{15}$	0.2509
F	3.0	$6.315\text{x}10^{11}$	5.0	$9.975\text{x}10^{14}$	0.2183
F2	3.0	$4.307\text{x}10^{11}$	5.0	$5.278\text{x}10^{14}$	0.2279
G	3.0	$2.477\text{x}10^{11}$	5.0	$2.138\text{x}10^{14}$	0.1793
W	3.0	$1.574\text{x}10^{11}$	5.0	$1.016\text{x}10^{14}$	0.1846

Allowable Stress Range

The probability density function $f(S)$ and cumulative distribution function $F(S)$ of the Weibull distribution of stress ranges S are expressed by:

$$f(S) = \frac{\xi}{k}(S/k)^{\xi-1}e^{-(S/k)^{\xi}} \tag{4a}$$

$$F(S) = 1 - e^{-(S/k)^{\xi}} \tag{4b}$$

The probability of exceedance $p(S)$ can then be expressed by

$$p(S) = 1 - F(S) = e^{-(S/k)^{\xi}}$$

and the number of cycles becomes

$$N = \frac{1}{p(S)} = e^{(S/k)^{\xi}}$$

or

$$\ln N = (S/k)^{\xi}$$

Based on the above expression, it can be shown that the stress range S_R determined at N_R cycles or $p = 1/N_R$ is related to the life-time stress range S_L determined at the life-time cycles N_L, or $p = 1/N_L$, by the following equation:

$$S_R = S_L\left(\frac{\ln N_R}{\ln N_L}\right)^{1/\xi} \tag{5}$$

Using the formula of the *simplified fatigue analysis* presented in the preceding section, the allowable stress range S_L for the design life can then be found as follows:

$$S_L = \frac{S_R}{D^{1/m}} \left(\frac{\ln N_L}{\ln N_R} \right)^{1/\xi} \tag{6}$$

The allowable stress ranges for a design life of 20 years for the eight U.K. DEn *Basic Design S-N Curves* were determined for a range of the Weibull shape parameter from 0.5 to 1.5, and the results are presented in Figure 2.

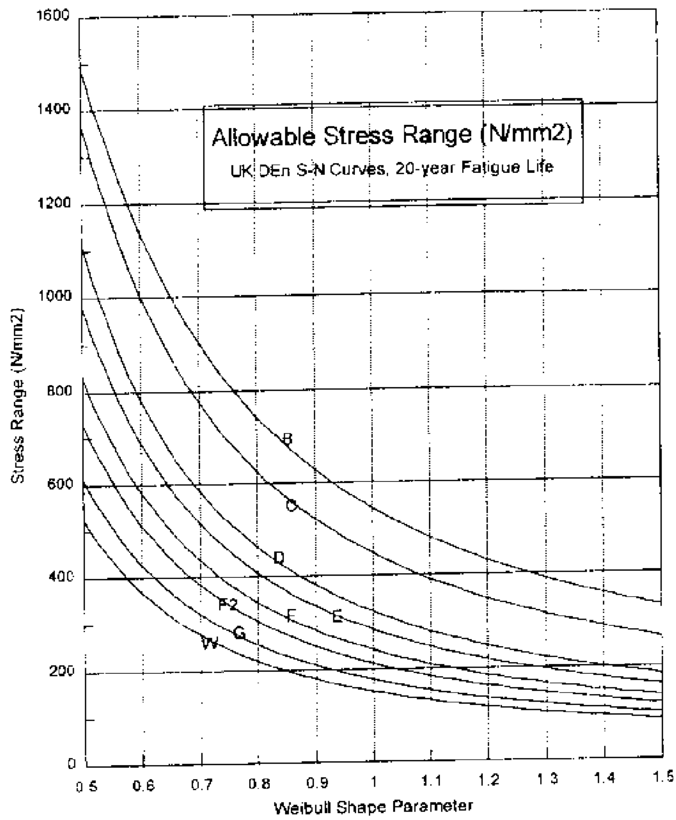


Figure 2. Allowable Stress Ranges for DEn Basic Design S-N Curves

Loads for Fatigue Strength Assessment

To determine the hull structural response, all loads with respect to the hull girder and local structures should be considered. These include static loads in still water, and wave-induced motions and loads. For the purpose of fatigue assessment, the structural response in still-water conditions is calculated separately to establish reference points for assessing the cyclic wave-induced structural response.

In the ***SafeHull*** approach, the eight standard combined load cases as defined in [4] are used for the structural analysis. The loading patterns of the eight load cases are shown in Figure 3 for three-cargo tank length portions of various tank configurations. For each load case, there are some necessary correlation factors and relevant coefficients for the loaded tanks. The static loads in the still-water conditions are determined in accordance with the loading patterns shown in the figure with the associated drafts and cargo and ballast loads. For each of the eight load cases considered, the loads specified represent the total loads that are the sum of static loads in still water and dynamic loads induced by waves. The difference between the total loads and the static loads are the wave-induced dynamic loads, that is

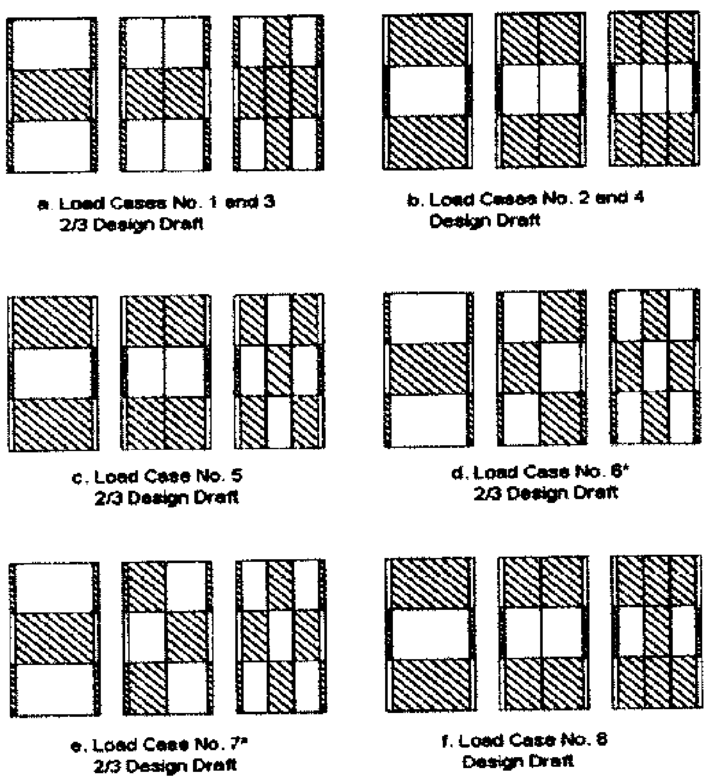
$$\textit{Dynamic Loads} = \textit{Total Loads} - \textit{Static Loads}$$

The resulting dynamic loads induced mainly by wave action and ship motions are:

i) "dynamic" hull girder loads (i.e., wave-induced vertical and lateral moments and shear forces, and torsional moment)

ii) external hydrodynamic pressure

iii) internal inertial and fluctuating loads.



*For tankers with an oiltight longitudinal bulkhead on the centerline where both cargo tanks, P&S, are anticipated to be loaded to the same filling level at all times, the calculated internal pressures on the longitudinal bulkhead may be reduced by multiplying by a factor of 0.6.

Figure 3. SafeHull Loading Patterns for Standard Load Cases of Tankers

For fatigue evaluation, only the stresses due to the above wave-induced "dynamic" loads are considered. These dynamic-load-induced stresses are taken as part of the cyclic stress ranges responsible for fatigue damage of the hull structure. The stress ranges are determined by combining the stresses determined by the "dynamic" loads of the eight cases into four pairs, load cases 1 and 2, 3 and 4, 5 and 6, and 7 and 8. For each load case, the fatigue-inducing "dynamic" stresses are obtained by deducting the static stresses due to still-water loads from the total stresses due to total loads.

For a given element or hot spot, the largest stress range of the four pairs is considered the *most probable extreme stress range* to be used for fatigue damage calculations in the *simplified fatigue analysis* approach. The *most probable extreme stress range* required in the *simplified fatigue analysis* is a direct result of the *most probable extreme loads* imposed on the hull structure. Each load component considered in the eight load cases is not necessary the most probable extreme value itself. Instead, the combined action of the various loads produces the most probable extreme values of stress range. Therefore, the various load components are generally combined with different phase angles for different parts of the hull structure.

Implementation of the Procedure

To provide a practical tool for the ***SafeHull*** fatigue assessment of the hull structure, a package of software was developed. A multi-step approach of FEA is utilized for this purpose, starting with the 3-hold hull girder structure, then the primary supporting structure and local structures under consideration, and finally the structural details of concern.

The computer program package consists of three parts: *3-hold FEA*, *local FEA*, and *fatigue evaluation*. The *3-hold FEA* analyzes the global response of the 3-hold hull girder under the total SafeHull loads as well as the static loads. The *local FEA* reads in or generates the local model, obtains automatically boundary displacements from the parent model, generates the 3D loads for the local model, solves the model for both total and static loads, and extracts displacements and stresses from the solved models. Furthermore, the program system, with FEMAP [6], graphically displays the loaded and unloaded model, and the solved model as well as tank loads.

For the *fatigue evaluation* part, stresses used may be from the *3-hold FEA* (if so desired), *local FEA* or a direct input of stress ranges (e.g., from phase A or other FEA). Design fatigue life may be a parameter specified by the user. Results of fatigue evaluation given by the programs include the most probable extreme stress ranges, the allowable stress ranges, fatigue lives, damage ratios, and failed structural element list, etc.

The computer program system allows three different ways to generate a local model: a "*user-prepared*" model, a "*zoom-in*" model, and the SafeHull model library. More details are given below:

1) *User-prepared Model*
The program system accepts a user prepared model, and the model is then converted into a SafeHull recognized format using either the SafeHull converters or FEMAP. The 3D model of a transverse web frame shown in Figure 4 is a "user prepared" local fine mesh model. The model covers two frame spaces, but the two end web frames were not be modeled because boundary displacements are imposed on the two end sections. The

model was "user prepared", but the majority of the data were automatically generated with the aid of the "*zoom-in*" tool.

2) *Zoom-in Tool*
   Utilizing the *"zoom-in" tool*, the user can benefit in two ways: (a) for creating a user-prepared model, the tool provides a basic model as a basis for further refinement in a quick and efficient way, and (b) when a geometrically-based model is built, and a finer mesh is desired, the tool is handy for mesh refinement. Figure 5 show a "zoom-in" model of the connection of the inner bottom and the sloping bulkhead of a double hull tanker. The model was created totally by the "zoom-in" tool.

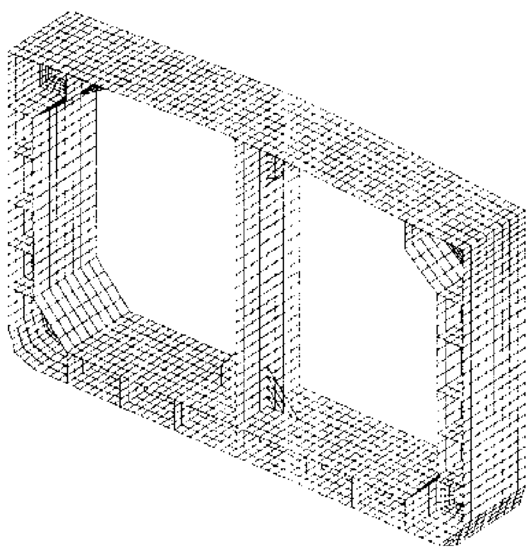


Figure 4. Local Model - Transverse Web Frame

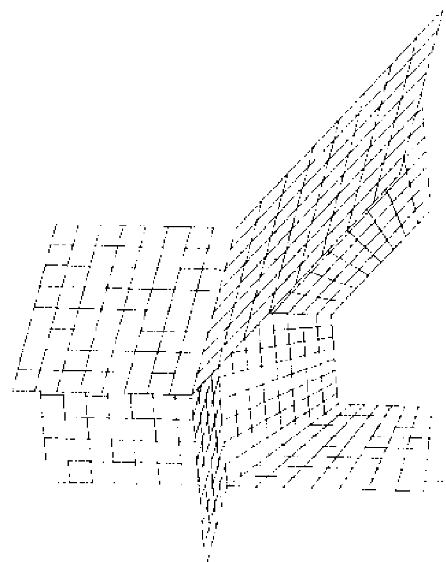
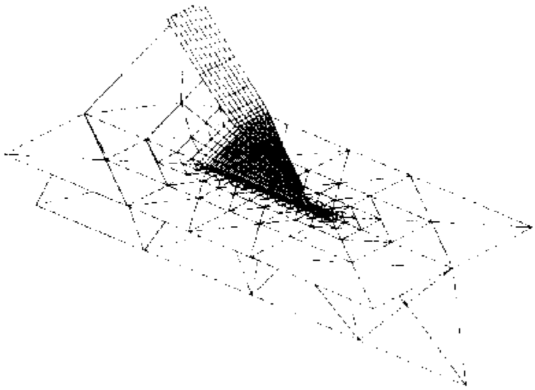
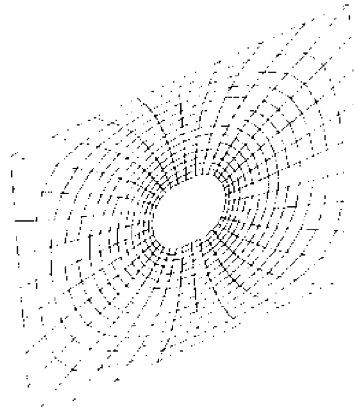


Figure 5. Local Model – Connection of Inner Bottom to Sloping Bulkhead

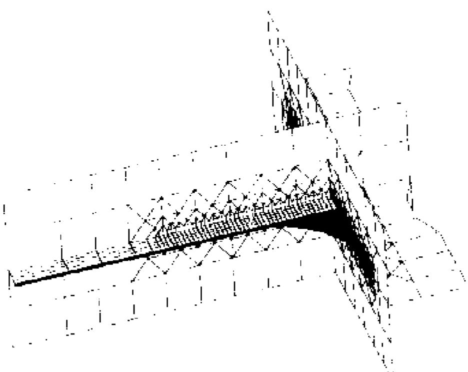
3) *SafeHull Model Library*
   The SafeHull system also provides a build-in model library for some typical structural details such as bracket toes, access holes, stiffener connections, and bulkhead connections. For each detail type, a parameter-controlled input file is used to automatically generate the desired model. The configurations of the model can be easily modified by changing the various parameters in the model input file. Figure 6 shows some local fine mesh models of typical details generated by the built-in SafeHull model library.



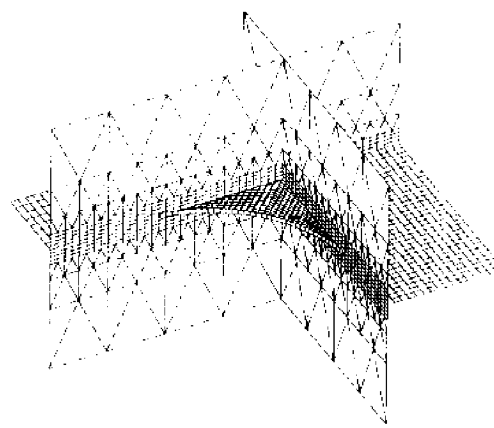
(a) Bracket Toe



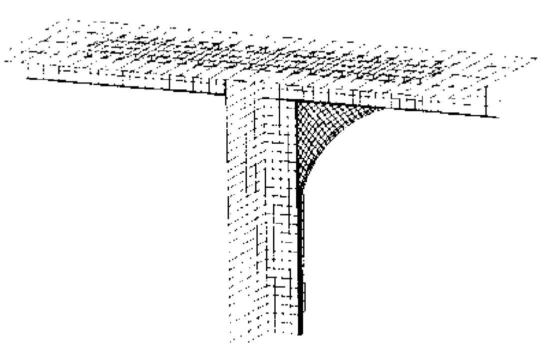
(b) Access Hole



(c) Stiffener Connection at Transverse and Longitudinal Bulkheads



(d) Connection of Transverse to Longitudinal Bulkheads



(f) Connection of Deck longitudinal to Transverse Bulkhead

Figure 6. SafeHull Model Library for Typical Structural Details

Application

As an illustration of utilizing the procedure described above, a fatigue analysis was performed for a 300,000-ton double hull tanker. To determine the global response of the hull structure, a coarse-mesh three-dimensional finite element model representing three cargo tanks of the hull girder structure within 0.4L amidships was used. The model is shown in Figure 7 with the deck and the end bulkhead removed for a better view of the internal structures.

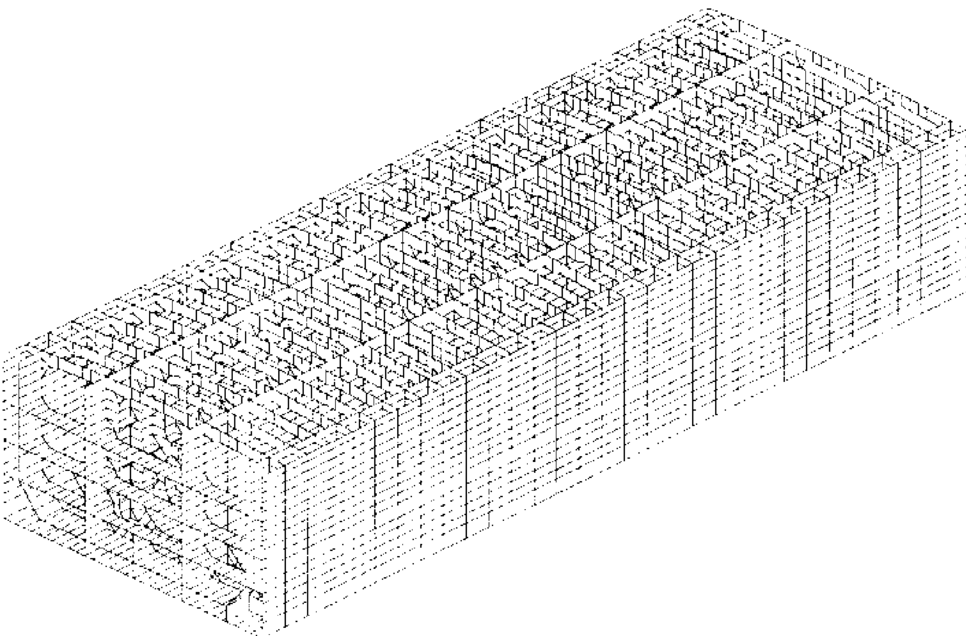


Figure 7. Three-hold Global Model of a VLCC

The 3-hold model was first analyzed by the total loads of the eight ***SafeHull*** standard load cases, and then by the still-water loads of the eight cases. The difference between the two stress results represents the amplitudes of the wave-induced fluctuating stresses.

To more accurately determine stress distributions in the transverse supporting structures, particularly at access holes and intersections of two or more structural members, four intermediate 3D fine-mesh models were made: one for the typical transverse web frame and three for the horizontal stringers on a transverse bulkhead. In making the 3D local models, relatively fine meshes were used to closely describe the geometry of the structure as well as the stiffness properties of the structure. Special attention was paid to account for the effect of stress concentration due to changes in geometry or in scantling in the high stress regions.

The multi-step analysis procedure that uses a coarse mesh global analysis followed by fine mesh local analysis, was used for the fatigue assessment. In this connection, boundary displacements instead of boundary forces were used as boundary conditions for the subsequent local models, because boundary displacements could be more readily applied. Application of local loads to the local models was done automatically by computer programs and they were consistent to that applied to the 3-hold global model.

Figure 8 shows a fine-mesh finite element model of the transverse web frame in the middle hold. This is actually a 3D fine mesh model that covers two frame spaces, similar to that shown in Figure 4, although only the middle transverse web frame is shown in the figure. The basic model was generated automatically by the "zoom-in" tool and then refined at the bracket end and cutout areas. For this 3D model, the required 3D internal and external pressure loads were generated automatically by the computer programs.

As can be seen, access holes on the transverse webs are properly modeled, and can be used for fatigue strength assessment of the access holes. The hot spots for the transverse web fine-mesh model required for the fatigue strength assessment are at the bracket end connections, around the access holes, and at the connections of the sloping bulkhead to inner bottom and side longitudinal bulkhead plating, as marked by circles in the figure.

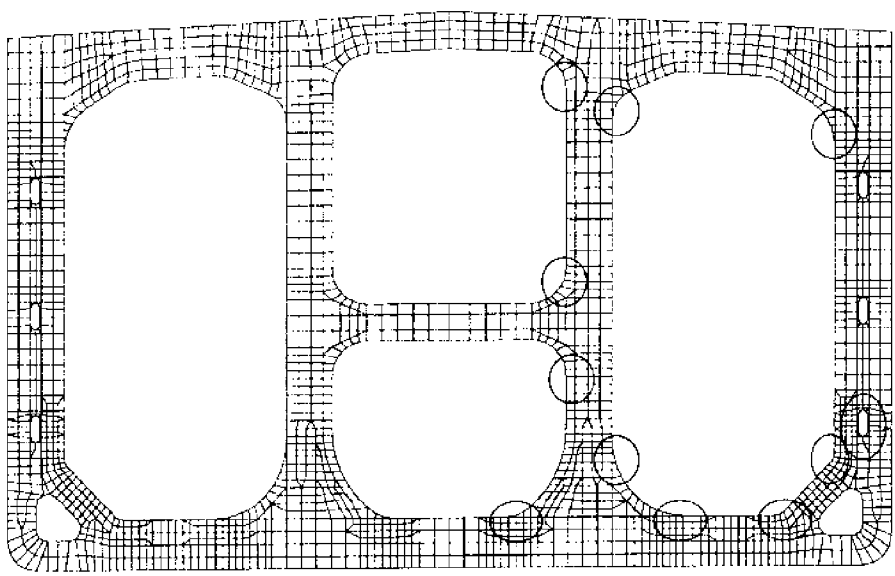


Figure 8. Intermediate Model of Transverse Web Frame

Figure 9 is an intermediate model of a middle horizontal girder on a transverse bulkhead. The model was first cut out directly from the three-hold model and then refined using the *zoom-in tool* with some modifications as described above for the web frame model. In this analysis, the stress ranges obtained in the model were screened for purposes of identifying the most fatigue-prone areas, which were then further analyzed by more detailed fine mesh models for closer fatigue assessment.

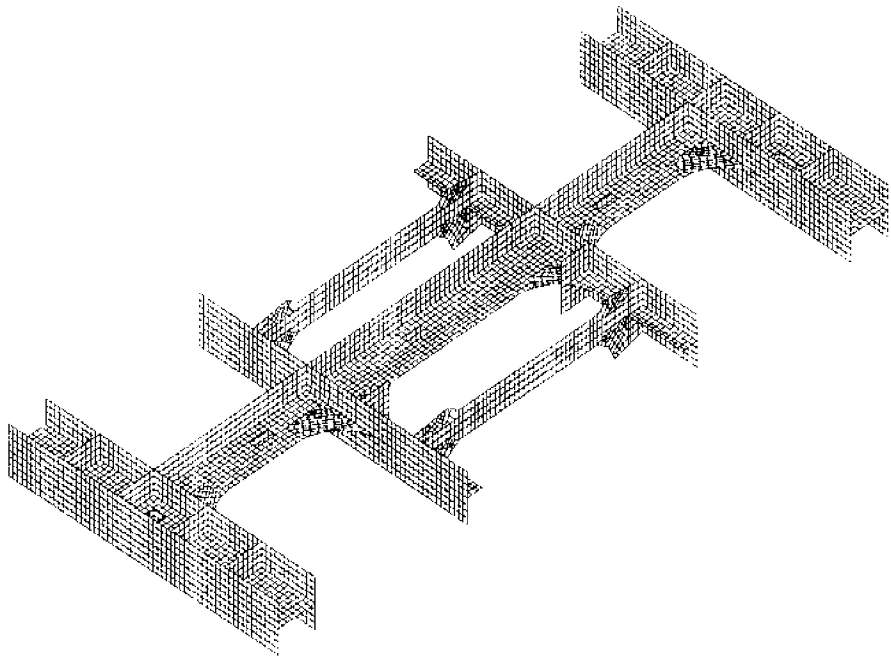


Figure 9. Intermediate Model of Transverse Bulkhead Horizontal Girder

The fatigue strength criteria specified in the Rules are based on the assumptions that all structural joints and welded details are properly designed and fabricated and are compatible with the anticipated working stress levels at the locations considered. It is important to closely examine the loading patterns, stress concentrations and potential failure modes of the structural joints and details in highly stressed regions. The structural performance of the structural details can be determined using fine-mesh models of the structural details with appropriate boundary conditions determined from the coarser mesh *local FEA* or from the global *3-hold FEA* directly if appropriate.

Fatigue life calculation is made directly from the calculated stress range with a specified S-N curve and an estimated Weibull shape parameter. Appropriate stress range, S-N curve and Weibull shape parameter should be specified for each of the ship structural details considered. The S-N curve and stress ranges to be used are closely related to each other. It is important to consider the stress and S-N curve simultaneously for the fatigue strength assessment in order to maintain consistency. For convenience, the ***SafeHull*** computer program calculates fatigue lives for all 8 classes of S-N curves for each element stress range, see Figure 11. The results are to be evaluated in accordance with the appropriate S-N curve for the structural detail considered.

Based on the procedures given in this fatigue guidance, the largest element stress range among the four pairs of the eight SafeHull standard load cases is considered as the *hot-spot stress range* for the element chosen for the calculation. Element stress ranges determined by the respective finite element models should be used in collaboration with appropriate S-N curves for the fatigue strength assessment.

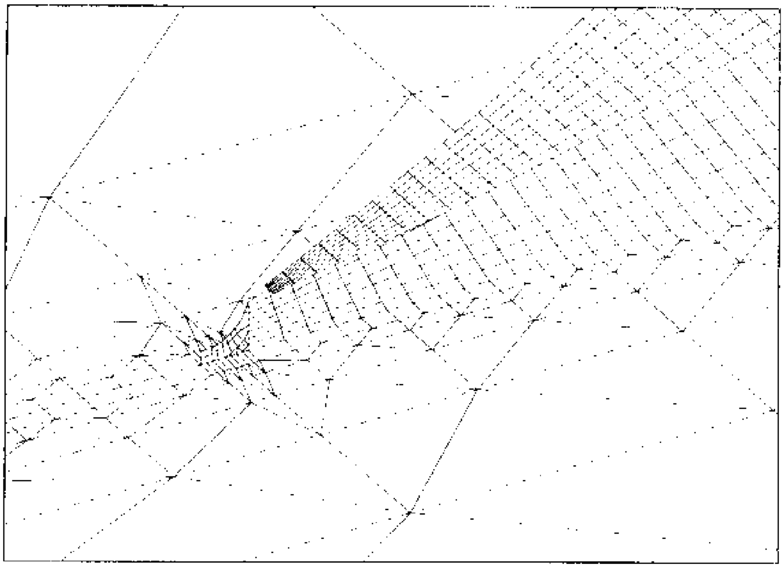
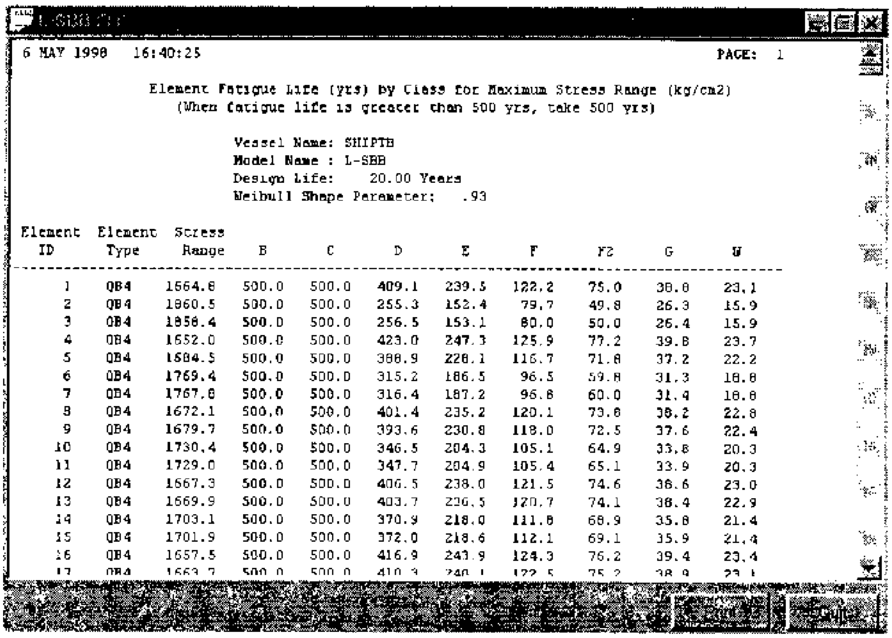


Figure 10. Enlarged View of the Toe End Area of a Bracket Toe Model

Figure 10 is an enlarged view of the toe end area of a bracket toe model generated by the SafeHull model library. Figure 11 shows some of the results on element fatigue life, along with the element stress ranges.



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Element Fatigue Life (yrs) by Class for Maximum Stress Range (kg/cm2)
(When fatigue life is greater than 500 yrs, take 500 yrs)

Vessel Name: SHIPTB
Model Name : L-SBB
Design Life: 20.00 Years
Weibull Shape Parameter: .93

Element ID	Element Type	Stress Range	B	C	D	E	F	F2	G	W
1	QB4	1664.8	500.0	500.0	409.1	239.5	122.2	75.0	38.8	23.1
2	QB4	1860.5	500.0	500.0	255.3	152.4	79.7	49.8	26.3	15.9
3	QB4	1858.4	500.0	500.0	256.5	153.1	80.0	50.0	26.4	15.9
4	QB4	1652.0	500.0	500.0	423.0	247.3	125.9	77.2	39.8	23.7
5	QB4	1684.5	500.0	500.0	388.9	228.1	116.7	71.8	37.2	22.2
6	QB4	1769.4	500.0	500.0	315.2	186.5	96.5	59.8	31.3	18.8
7	QB4	1767.8	500.0	500.0	316.4	187.2	96.8	60.0	31.4	18.8
8	QB4	1672.1	500.0	500.0	401.4	235.2	120.1	73.8	38.2	22.8
9	QB4	1679.7	500.0	500.0	393.6	230.8	118.0	72.5	37.6	22.4
10	QB4	1730.4	500.0	500.0	346.5	204.3	105.1	64.9	33.8	20.3
11	QB4	1729.0	500.0	500.0	347.7	204.9	105.4	65.1	33.9	20.3
12	QB4	1667.3	500.0	500.0	406.5	238.0	121.5	74.6	38.6	23.0
13	QB4	1669.9	500.0	500.0	403.7	236.5	120.7	74.1	38.4	22.9
14	QB4	1703.1	500.0	500.0	370.9	218.0	111.8	68.9	35.8	21.4
15	QB4	1701.9	500.0	500.0	372.0	218.6	112.1	69.1	35.9	21.4
16	QB4	1657.5	500.0	500.0	416.9	243.9	124.3	76.2	39.4	23.4
17	QB4	1663.7	500.0	500.0	410.3	240.1	122.5	75.2	38.9	23.1

Figure 11. Element Fatigue Life

During the illustrative analysis, about thirty structural details were evaluated. The fatigue results indicated that there were only two locations where a specified 30-year design life was not satisfied – one at the bracket connecting the deck transverse to the longitudinal bulkhead, and the other at the bracket of the middle horizontal girder connecting to the longitudinal bulkhead. The analysis further indicated that a 2 mm increase in thickness of the bracket in the toe end area would sufficiently raise the fatigue life to meet the target life.

Conclusion

SafeHull FEM fatigue analysis procedure using the so-called "simplified fatigue analysis" with the SafeHull standard load combinations provides a practical approach to fatigue strength assessment of the hull structure. The procedure can be performed in conjunction with routine finite element stress analysis, in lieu of more elaborate methods such as spectral fatigue analysis, to evaluate the fatigue strength of the complex hull structure. The practical tool is very useful to aid engineers in the design or repair process to assess fatigue performance of ship structural details and welded connections.

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SIMPLIFIED STRESS ANALYSIS OF SHIP STRUCTURES

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Abstract

The American Bureau of Shipping (ABS) recently completed a study to develop a streamlined approach to the finite element analysis (FEA) of ship structures that simplifies the process without causing appreciable loss in the accuracy of stress prediction. The results of this study lead to recommended guidelines for FEA modeling and analysis of ABS-classed tankers, bulk carriers and containerships. Clearly, such guidelines used in conjunction with well-established SafeHull analysis procedures can lessen the need for engineering judgement, ensure a similar stress evaluation regardless of who performs the analysis and reduce the time required to complete an FEA evaluation.

The study establishes a baseline result by analyzing a detailed structural model created with as few simplifying model idealizations as possible. Various simplifying techniques are then studied and compared to the baseline result and two simplified approaches are presented. The ABS SafeHull analysis and structural yielding/buckling evaluation procedures are discussed to provide more information about this study.

One recommended procedure is a two-step approach. First analyze a coarse mesh 3D model to assess hull girder strength and to determine accurate displacements. Then local 3D fine mesh models of principal supporting members such as web frames and horizontal girders are analyzed and evaluated under the loads and subjected to the displacements computed in the first step. An alternative procedure is a one-step approach. Creating a fine mesh 3D model that contains sufficient detail such that few or no local 3D models are required. The one-step results are used to assess both hull girder strength and evaluate stress in principal supporting members.

Introduction

Using the FEA approach to compare the strength of a ship structure to the failure criteria for yielding, buckling and fatigue (strength assessment) is often time consuming even for an experienced analyst. To perform such an evaluation, an engineer must carefully create an accurate FEA model, apply loads, run the analysis and assess the results. There are many options available to simplify the assessment procedure such as reducing the size of the finite element model, automating loads application and breaking the task into one global analysis followed by a series of local detailed analyses.

Although the use of a higher mesh density and more structural detail will result in the most accurate stress predictions, such a model is much more time consuming to create, more prone to error during model creation and requires more computer resources to solve. However, if an insufficient number of elements are used, the structure will lack the correct flexibility leading to inaccurate results.

ABS has developed the load and strength criteria, which are based on a first principles approach. This means that the appropriate loads are determined for a structural member first, then the stress response to those loads is determined. Dynamic global loads and local pressures, and their combined effects are considered in strength and failure criteria [1], [2], [3] and [4]. The ten critical load cases have been developed to evaluate ship strength at different structural locations. Accordingly, a loading procedure has been implemented in the ABS SafeHull system to automatically apply these loads to an FEA model. To evaluate hull girder strength using finite element models of coarse mesh density, SafeHull can perform local bending stress calculations due to local pressure load after the finite element solution is obtained.

One simplified approach to ship strength assessment is to first analyze a coarse mesh three-hold model for the evaluation of hull girder strength and to obtain accurate displacements. Then, local detailed 3D models of principal supporting members such as transverse structures or horizontal girders can be analyzed in which the mesh density is increased, the detailed geometry considered and displacements calculated in the first step are applied as boundary conditions. An alternative approach is to analyze a fine mesh three-hold model that contains sufficient detail to reduce or eliminate the number of required local analyses.

Clearly, there is a need to study modeling approaches, loading procedures and simplifying assumptions to produce a set of recommended FEA analysis guidelines for ship structural analysis. To verify the simplification process, a very detailed 3D three-hold model was created and analyzed. This detailed 3D fine mesh model has the same mesh size as a model required for local detailed stress analysis [5] and is used as the "baseline" result. Various simplified models are then analyzed and results are compared with the baseline result.

One of the objectives of this study is to provide these comparative results as a reference for ship analysts. The main goal for this study is to develop a streamlined modeling and analysis procedure for ship structural analysts, thereby reducing the time required to complete the evaluation of a ship design. The paper primarily studies the effects of simplifying assumptions on global 3D and local detailed models.

Analysis Approach

One proven technique for obtaining accurate stress distribution in principal supporting structures of ships such as web frames is the "two-step" method. This technique is very useful in situations where computer resources are limited. First a coarse mesh 3D global model of a three-hold section is created. This model can consist of element sizes equal to the spacing between transverse frames in longitudinal direction and every two or three (recommended two) longitudinal stiffeners in transverse direction with lumped stiffeners. The typical 3D three-cargo hold global coarse mesh models for tanker, bulk carrier and containership are shown in Figures 1, 2 and 3, respectively. This coarse mesh model can then be analyzed by

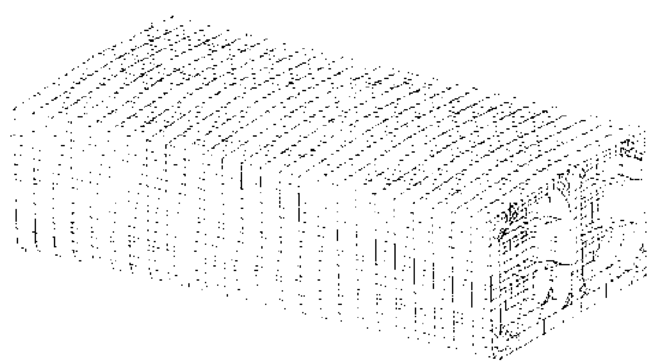

Figure 1. A Typical 3D Global Coarse Mesh Tanker Model

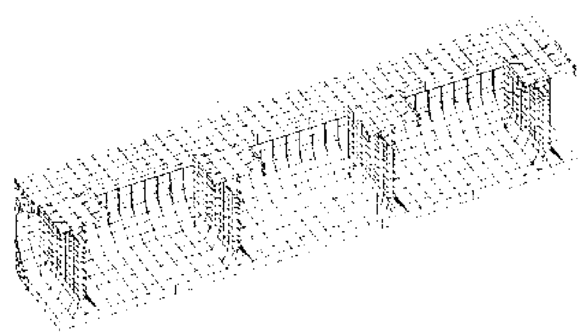

Figure 2. A Typical 3D Coarse Mesh Bulk Carrier Model

applying the hull girder load in terms of cargo load, ballast load and external wave load. In the second step, a series of more detailed local fine mesh models of the principal supporting structures of interest are loaded and subjected to the boundary conditions calculated in the 3D global analysis. Usually, a dozen or more local model is required to ensure thorough structural strength checks.

An alternative approach is the "one-step" method. In this approach, a fine mesh 3D global model is created that contains sufficient detail to eliminate the need for much or all local analyses. Typically, this 3D fine mesh model includes all stiffeners at their design locations, by which the mesh size will be determined. Element aspect ratio should be considered to determine the mesh size for those areas that are not governed by stiffeners. In certain detailed or large stress areas, such as a cutout, bracket toe and the structural connections, a more detailed mesh size may be needed to accurately compute stress variations. A typical one-step fine mesh model is shown in Figure 4.

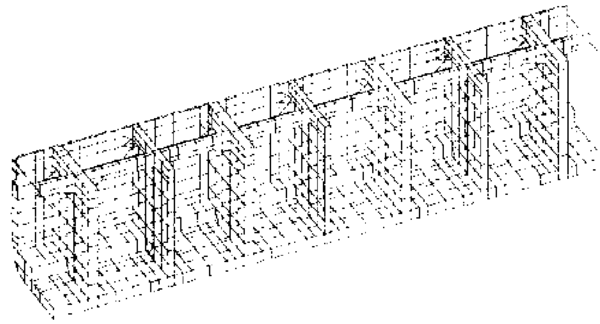

Figure 3. A Typical 3D Coarse Mesh Containership Model

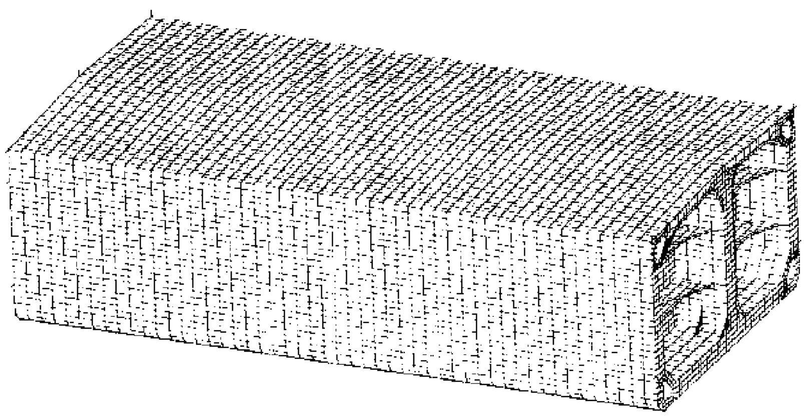

Figure 4. A Typical 3D Fine Mesh Tanker Model

Because this study compares the effect of certain simplifying

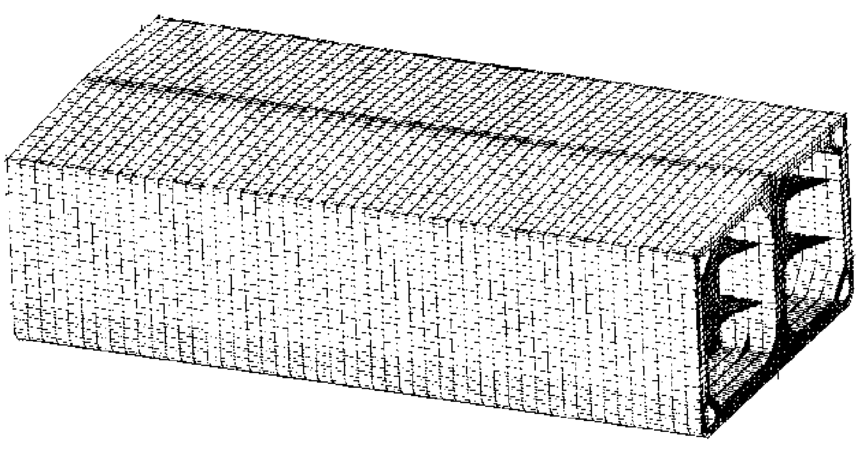

Figure 5. A Very Detailed 3D Fine Mesh Tanker Model

assumptions on stress prediction, a very detailed three-hold model has been created, as shown in Figure 5, and analyzed. This model contains two plate elements between frames and two elements between longitudinal stiffeners. The plate elements are defined as bending elements and all plate stiffeners are included and modeled as beams.

3D Global Model Analysis

A finite element analysis of a ship structure focuses on the most critical portion of the structure, that being the three-cargo-hold midship section. This requires the application of proper boundary conditions and load criteria such that the stress from this model can be used for strength evaluation. At ABS, such a study has been undertaken based on the first principles approach, and the load and strength criteria have been established which can be found in ABS Rules [6]. The strength assessment involves the hull girder strength and local strength assessment of ships, which mainly focus on yielding, buckling and fatigue evaluation. A 3D three-hold midship model analysis approach has been developed and primarily serves for hull girder strength assessment.

The hull strength, in terms of the moment of inertia of the entire cross section area, will not be affected by modeling plates as bending or membrane elements and stiffeners as rod or beam elements. Therefore, the primary stress due to hull girder bending and secondary stress of stiffened panels deformed under local loads between transverse bulkhead will remain essentially the same for a model with either bending plate and beam combination or membrane plate and rod combination of longitudinal members [5]. Strength evaluation for all longitudinal members can be obtained from a simplified 3D coarse mesh model, because SafeHull accounts for additional stress due to local pressure load on local stiffeners (offset) and plate bending. For longitudinal strength evaluation, transverse structures can be simply modeled by only considering plate elements and a few important stiffeners.

To study the different element combinations, three different models for the same tanker vessel have been built. The principal dimensions of this vessel can be found in Table 1. These three models are:

a) a model with membrane plate and rod combination.
b) a model with bending plate and rod combination
c) a model with bending plate, rod and beam combination.

Table 1. Principal Dimensions

Length, B.P.	266.365 (m)
Breath, Moulded	45 (m)
Depth, Moulded	25 (m)
Draft, Design	18 (m)
Block Coefficient Cb	0.85

A total of ten SafeHull load cases are applied to these three models, in which each load condition represents SafeHull load criteria for different structural sections. Yielding and buckling evaluation are performed and represented by yielding and buckling factors, which are the ratio of calculated stress against SafeHull strength criteria. Tables 2 and 3 show the SafeHull yielding factors for maximum load case at each location for the tanker model with different element type combinations, shown in Figure 1. The model has coordinates of x-forward, y-upward and z-toward starboard with the origin at the intersection of bottom, center plane and frame 1 (shown in Figure 6).

The panels for yielding and buckling checks have been selected between frames 13 and 14 as shown in Figure 6. It can be seen that from Tables 2 and 3 the differences of yielding and buckling between different models are very small. However, three models will result in different displacement boundary conditions for local 3D analysis. The model a) can only produce translational displacements since only membrane plate and rod elements are used. The model b) can provide both translational and rotational displacements because of bending plates are used. However, only those rotational displacements are considered reliable at those planes where the plates connect (back up) to each other orthogonally, such as on a transverse web frame plane, where no beams are present. The model c) should provide both reliable translational and rotational displacements.

Table 2. Comparison of Yielding Factors for the Tanker with Three Different Combinations

Models \ Panel Location	Bottom (Z=14)	Shell (Y=14)	Deck (Z=14)	Inner Skin (Y=12)
Membrane & Rod	0.68 (LC-1)	0.42 (LC-6)	0.77 (LC-1)	0.83 (LC-7)
Bending Plate & Rod	0.68 (LC-1)	0.42 (LC-6)	0.77 (LC-1)	0.83 (LC-7)
Bending plate & Beam	0.66 (LC-1)	0.42 (LC-6)	0.76 (LC-1)	0.84 (LC-7)
One Step Model	0.66 (LC-1)	0.41 (LC-6)	0.76 (LC-1)	0.79 (LC-7)

Table 3. Comparison of Buckling Factors for the Tanker with Three Different Combinations

Models \ Panel Location	Bottom (Z=14)	Shell (Y=14)	Deck (Z=14)	Inner Skin (Y=25)
Membrane & Rod	1.06 (LC-2)	0.54 (LC-8)	1.01 (LC-1)	1.12 (LC-1)
Bending Plate & Rod	1.06 (LC-2)	0.54 (LC-8)	1.01 (LC-1)	1.15 (LC-1)
Bending plate & Beam	1.06 (LC-2)	0.51 (LC-8)	0.96 (LC-1)	1.10 (LC-1)
One Step Model	1.20 (LC-2)	0.52 (LC-8)	0.97 (LC-1)	1.13 (LC-7)

On the other hand, solving a 3D global model with a mesh size as shown in Figure 1 is no longer a big job with today's computing power. Table 4 shows the solution time required for 3D global coarse mesh model with MSC/NASTRAN [8] on a Pentium 350 MHz PC. In order to obtain a good design, the ship structure analysis is usually an iterative process (re-analysis). The quick FEA analysis time required to solve the 3D coarse mesh model make the iteration process much less time consuming.

Table 4. Comparison of FEA Analysis Time among Models with Different Mesh Density

Models	3D Coarse Mesh Model	One Step Fine Mesh Model	Very Fine Mesh Model
Nodes	8,966	33,746	69,478
Element	17,610	77,440	128,942
Solution time	11m35s	1h48m35s	2h18m34s on SGI Workstation

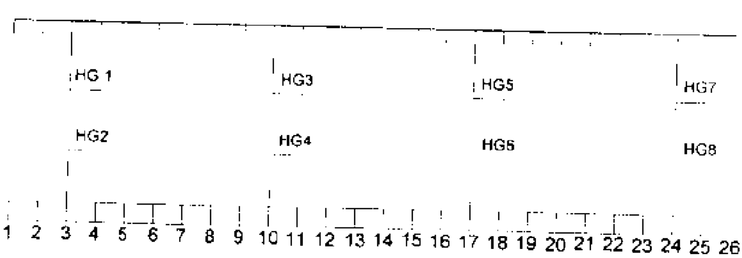

Figure 6. Frame Arrangement of the Tanker Model

Local Detail Model Analysis

A local detail model should be created for the principal supporting structure of interest in the case where the global model is of insufficient mesh density. The typical local fine mesh models for transverse web frame structure and horizontal girder are shown in Figures 7 and 8, respectively. The accuracy of the results from such a local analysis is mainly dependent on the modeling of local details and the boundary conditions obtained from the global analysis, provided that the correct loads have been applied. The local model should be at least as fine as the one-step fine mesh model, described previously. Finer mesh density may be needed for local details such as a bracket toe or cutout [5].

Many such detailed models may be needed to assess all critical ship locations, such as transverse web frames, horizontal and longitudinal girders, double bottom girders and floors, connection of corrugated bulkhead, inner bottom and low stool area, etc. The number of local models required for local detail stress analysis will vary from different designs and vessel types. The creation of all local 3D models is time consuming. Hence, an automatic zooming procedure has been developed by ABS to generate a local detail model by cutting and refining the part of interest from the 3D global model.

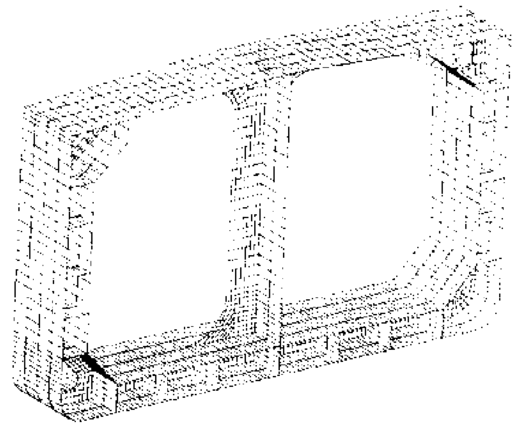

Figure 7. A Typical 3D Local Fine Mesh Model for Transverse Web Frame Analysis (Tanker)

The three simplified 3D global models discussed in the previous section may lead to different boundary conditions for the local 3D analyses, especially nodal rotations. The motivation to use the combination of membrane plates and rods in the three-hold model is that with only in-plane translational degrees of freedom, the element stiffness matrices are reduced by a third and the solution time is reduced by a factor of nine. However, if a local detail model is then created with beam elements as stiffeners and the nodal rotations on the cut boundary are unknown, inaccuracy in the displacements and stresses in the local model may be introduced.

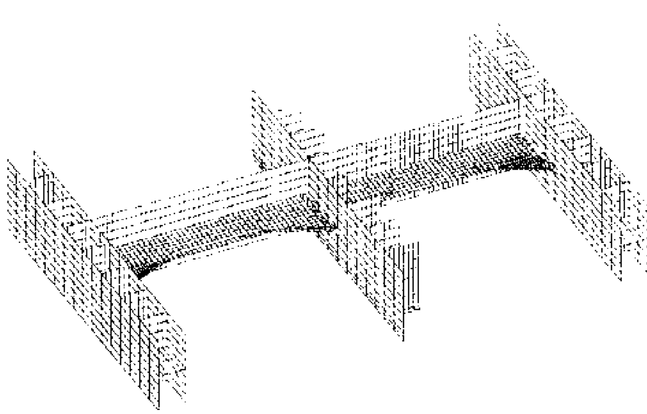

Figure 8. A Typical 3D Local Fine Mesh Model for Horizontal Girder Analysis (Tanker)

Critical Stress Area

Critical stress areas for a ship structure [7] are generally located at points of sudden geometric change and structural connection areas. Figures 9 and 10 show the stress distribution and some critical stress areas (shown by circles) for a transverse web frame and horizontal girder, respectively, in a tanker model.

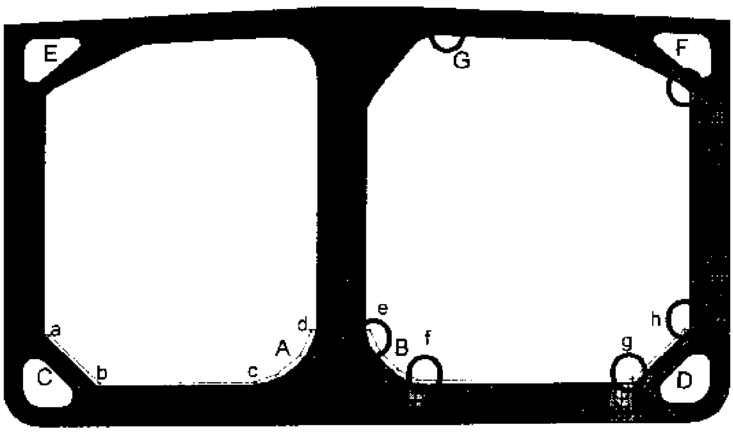

Figure 9. Critical Stress Areas for Transverse Web Frame (Tanker)

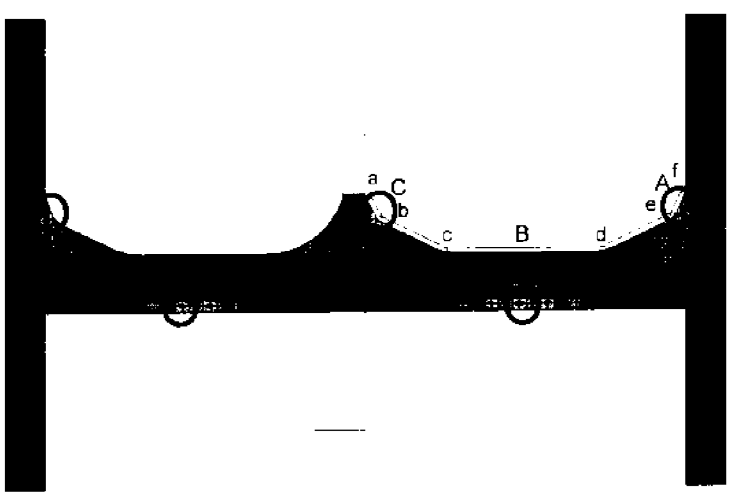

Figure 10. Critical Stress Areas for Horizontal Girder (Tanker)

Such critical stress areas should be considered when determining the mesh density. For example, a 3D global coarse mesh model should contain more elements in these areas to provide a good estimation for determining if local detail stress analysis is necessary. If a one-step analysis is performed, element density in these areas should be much finer. Otherwise, local detail stress analysis cannot be eliminated.

Comparison Study

There are many modeling simplifications that the analyst can make to approximate a solution, thereby making the best use of modeling time, computer efficiency and data storage. However, certain simplifying assumptions can lead to incorrect predictions of displacement and stresses. This study looks at the effects of making certain modeling assumptions in an effort to find a procedure that lessens the need for engineering judgement in the evaluation of stress. These variations include:

- Distribution of the applied load
- Element type
- Specification of boundary conditions
- Omission of stiffeners

Because this study compares the effect of certain simplifying assumptions on stress prediction, the first step is to create and analyze a very detailed three-hold baseline model, which has been shown in Figure 5. This model meets the mesh density criteria for local stress analysis as required [5] and has a mesh density identical to the local 3D fine mesh models. Actually, the local 3D models, as shown in Figures 7 and 8, are cut from this fine mesh model. Therefore, the comparison for the element stress is based on identical FEA models. As shown in Table 4, this model contains a total of 69,478 nodes and 128,942 elements. The model was solved in 2.3 hours of elapsed time by MSC/NASTRAN on a SGI UNIX workstation.

For the purpose of comparison, the most critical transverse web (frame 15) and one horizontal girder (HG4) were selected, as depicted in Figure 6. The stress areas for comparison for the web frame are labeled as A through G and are annotated in Figure 9, and for the horizontal girder are labeled as A through C and are annotated in Figure 10. For each of the ten load cases studied, the maximum stresses (corresponding to maximum load case) in these high stress regions are used throughout this report to assess the deviation in accuracy due to certain simplifying assumptions. The result from the very fine mesh model is represented by Baseline and is normalized to 1. The ratios between stresses from other models to the baseline model are used for comparison.

Load Distribution

The local 3D model can contain nodes that are neither on the cut boundary nor in the plane of interest. For this reason, there is an option either to apply loads to all nodes (distributed loads) or to simply apply a lumped line load only on the nodes in the 2D plane of interest (line load). This study finds that if the local detail model contains longitudinal stiffeners and nodal rotations on the boundary are specified, either the distributed load or the line load leads to essentially the same result (Table 5).

Table 5. Stress Comparison on Frame 15 - Distributed Load versus Line Load

Location and Load Case	A:LC6	A:LC7	B:LC6	B:LC7	F:LC7
Baseline	1	1	1	1	1
Distributed Load	1	0.99	0.98	0.98	0.96
Line Load	1.01	0.99	0.98	0.98	0.96

Special consideration is needed for the horizontal girder. In the case there is no beam elements in global 3D model, the rotation boundary conditions on a cut boundary are only reliable at locations which have longitudinal support. For example, the local model for HG4 has to be extended to HG3 and inner bottom, which will produce a deeper model than is shown in Figure 8. Only then will the local analysis produce reasonable results using distributed load and specified rotational constraint on the cut boundary. Otherwise, a line load must be used to eliminate any rotational effects. Table 6 shows the comparison, in which the distributed load has been applied to a "larger" local 3D model and line load has been applied to a "short" local 3D model.

Table 6. Stress Comparison on Horizontal Girder HG4 - Distributed Load versus Line Load

Location and Load Case	A:LC6	A:LC7	B:LC5	C:LC3	C:LC7
Baseline	1	1	1	1	1
Local 3D – dist. load	0.83	0.87	1.02	0.97	0.99
Local 3D – line load	0.94	0.99	1.02	0.91	0.94

In the case where the local 3D mesh is of such refinement that there are two or more elements between longitudinal stiffeners, some nodes between the longitudinal stiffeners will be loaded. The vertical stiffness against such a load will differ depending on the existence of a stiffener at that node location. Such a situation will create a stepped phenomenon in the web shear and Von Mises stress. This is a local effect and does not exist in the case of lumped line loading.

Element Type

The local bending effects are important and need to be included for local stress predictions. Therefore, bending plate elements should be always used in the local 3D model. The advantage of using the bending plates in the 3D global model is that reasonable nodal rotations are calculated at those planes with back up plates. These planes can be used as the cutting boundary of the local detail model. Applying both translational and rotational boundary conditions for the local detail analysis will improve the local stress prediction.

One timesaving technique that can be used is to model the lumped stiffeners as rods rather than beams in the 3D global coarse mesh model. This will not affect the hull girder strength evaluation (Tables 2 and 3). Because we are interested in only the global displacement, it is the axial stiffness and not bending in the stiffener that is important, while the bending plate will pick up the nodal rotations needed for the local 3D analysis. In addition, a rod property is defined much more easily than a beam property that requires the moments of inertia and orientation data to be defined.

Table 7 shows the stress comparison between the baseline model (Figure 5) and the 3D local model (with stiffeners) using boundary conditions from three different 3D coarse mesh models (described in the Section 3D Global Model Analysis). The normalized maximum stress (under line load) for certain load cases at different locations is presented.

Table 7. Stress Comparison on Frame 15 - Element Type in 3D Coarse Mesh (Line Load)

Location and Load Case	A:LC6	A:LC7	B:LC6	B:LC7	F:LC7
Baseline	1	1	1	1	1
Membrane & Rod	0.93	0.89	0.93	0.88	0.94
Bending & Rod	0.94	0.92	0.95	0.91	1.03
Bending & Rod & Beam	1.01	0.99	0.98	0.98	0.95

It can be seen that from Table 7 the element types used in the 3D global model will affect the 3D local detail stress analysis results. The global model with membrane and rod combination lead to a large difference in local stress calculation since rotational displacements are not computed in the global analysis.

Specification of Boundary Conditions

When a local 3D model of a principal supporting structure is created for detailed stress analysis, the displacements computed from the three-hold analysis must be applied to the cut boundary. If additional nodes are created because of mesh refinement such that no corresponding node exists in the three-hold model, specified displacements on the cut boundary can be interpolated linearly for those nodes. If nodal rotations are computed in the three-hold analysis, they should be included in the specified displacements applied to the local 3D model. Otherwise, the nodal rotations on the cut boundary should be left free to ensure a conservative stress estimate.

To study the boundary condition effects, the frame 13, as shown in Figure 6, was selected since it is close to transverse bulkhead and the horizontal girders HG3 and HG4. The data in Tables 8 and 9 show that whether the rotations should be left free or constrained is dependent on the local area of concern and no general guideline can be discerned. For this reason, it is best to use bending plates in the global 3D model such that nodal rotations can be specified in the local 3D analysis. However, it should be mentioned here again that without beam elements present in the 3D coarse mesh model, only those rotations at locations where "back-up" support exists could be meaningful.

Table 8. Rotation boundary effect at Frame 13 (Distributed Load)

Location and Load Case	A:LC6	A:LC7	B:LC6	B:LC7	F:LC7
Baseline	1	1	1	1	1
Rotation Free	1.18	1.17	1.11	1.14	1.08
Rotation Fixed	1.01	1.01	0.97	0.97	0.96
Rotation Specified	1.04	1.03	1.02	1.01	1.05

Table 9. Rotation boundary effect at Frame 15 (Distributed Load)

Location and Load Case	A:LC6	A:LC7	B:LC6	B:LC7	F:LC7
Baseline	1	1	1	1	1
Rotation Free	1.03	1.01	1.02	1.01	1.05
Rotation Fixed	0.85	0.84	0.87	0.85	0.94
Rotation Specified	1.01	0.99	0.98	0.98	0.96

Longitudinal and Transverse Stiffeners

The mesh density of the local 3D model should be of sufficient size such that all longitudinal and transverse stiffeners can be included with no lumping required. Table 10 shows the effect of existence of longitudinal stiffeners. Table 11 shows that the effect of omitting stiffeners (transverse stiffeners) in the plane of interest. Only rods on faceplates and stiffeners parallel to the direction of principal stress need to be included.

Table 10. Stress Comparison on Frame 15 - Existence of Longitudinal Stiffeners

Location and Load Case	A:LC7	B:LC7	C:LC6	D:LC7	F:LC7	G:LC7
Baseline	1	1	1	1	1	
With longitudinal stiffener Line load, Rotations specified	0.99	0.98	0.97	0.96	0.96	1.02
With longitudinal stiffener Line load, Rotation free	0.89	0.88	0.79	0.85	0.94	0.87
W/o longitudinal Stiffeners Line load, Rotation specified	0.96	0.96	0.97	0.94	0.96	0.95
W/o longitudinal stiffener Line load, Rotation free	0.96	0.97	0.97	0.94	0.97	0.95

This study shows that the inclusion of longitudinal stiffeners can improve the stress predictions, in the case the rotation boundary from 3D global is available. If the load is applied only in the plane of the web (line load) and without rotational boundary condition specified, longitudinal stiffeners should be removed. It can be seen that transverse stiffeners are not critical for the stress predictions at the interested locations.

Table 11. Stress Comparison on Frame 15 - Existence of Transverse Stiffeners

Location and Load Case	A:LC7	B:LC7	C:LC6	D:LC7	F:LC7	G:LC7
Baseline	1	1	1	1	1	1
With all stiffeners Dist. load, Rotation specified	0.99	0.98	0.98	0.96	0.96	1.03
W/o transverse stiffeners Dist load, Rotation specified	0.99	0.98	0.98	0.96	0.96	1.01
With all stiffeners Line load, Rotation specified	0.99	0.98	0.97	0.96	0.95	1.02
W/o transverse stiffeners Line load, Rotation specified	0.99	0.98	0.97	0.96	0.95	1.01

The One-Step Method

A 3D global coarse mesh model cannot be used for predicting local detail stresses. One alternative is to use a single fine mesh model to perform a one-step analysis. The one-step 3D model should include as much detail as possible for evaluating all structural strength such that few, if any, local models will be required. The three-hold model should consist of bending plates and all longitudinal stiffeners modeled as beams. Most other stiffeners can be omitted except in local areas where the stiffener is parallel to the principal direction of stress [7]. The finite element size should be at least half frame space in the longitudinal direction and one space between longitudinal stiffeners.

It has been shown in Tables 2 and 3 that the one-step fine mesh model will provide results very close to those from the 3D global coarse mesh model used for hull girder strength evaluation. In addition, Tables 12, 13 and 14 show that the stress results in the critical areas for the transverse web frames and the horizontal girder compare very well with the baseline results. Ratio variations in excess of 5% at some locations are due to mainly geometric accuracy. The simplified one-step model is the model without most transverse stiffeners on the transverse web frames.

However, it can be seen that such a model, shown in Figure 4, consists of 33,746 nodes and 77,440 elements. Even for the simplified one-step model, there are still 65,258 elements and the same number of nodes. Hence, the processing for strength evaluation, including creating the model, preparing loads, FEA analysis and post processing is much longer than that for the 3D global coarse mesh model. As shown in Table 4, the solution time for the one-step fine mesh model has been increased about 10 times, which will prolong the iteration process. In addition, local 3D detail models may still be required if a one-step model is not fine enough for some local areas.

Table 12. Frame 13 – One-Step versus very Fine Mesh (Baseline)

Location and Load Case	A:LC7	B:LC7	C:LC6	D:LC7	E:LC4	F:LC7	G:LC7
Baseline Model	1	1	1	1	1	1	1
One-step Model	0.97	1.01	0.98	0.95	1.07	1.11	1.16
Simplified One-step Model	0.99	1.03	0.98	0.96	1.06	1.11	1.17

Table 13. Frame 15 – One-Step versus very Fine Mesh (Baseline)

Location and Load Case	A:LC7	B:LC7	C:LC6	D:LC7	E:LC4	F:LC7	G:LC7
Baseline Model	1	1	1	1	1	1	1
One-step Model	1	1	0.98	0.96	1.12	1.09	1.16
Simplified One-step Model	1	1.01	0.98	0.96	1.12	1.10	1.14

Table 14. Horizontal Girder – One-Step versus very Fine Mesh (Baseline)

Location and Load Case	A:LC6	A:LC7	B:LC5	C:LC3	C:LC7
Baseline Model	1	1	1	1	1
One-step Model	1.05	1.10	0.97	0.97	0.94
Simplified One-step Model	1.06	1.10	1.97	0.98	0.91

Recommended FEA Procedure

The stress comparisons presented have shown that the results from the one-step fine mesh model are close to those from the very fine mesh model (baseline). If computer resource is available, the one-step approach is recommended because this approach will reduce the need for further local analysis. If the analyst knows ahead of time which principal supporting members are to be checked, such as those shown in Figure 9, those particular members or structural areas should contain extra geometric detail or a finer mesh. Otherwise, additional local detail analysis may be required.

For the case where a two-step approach is used, the following recommendations apply:

Global Three-Hold Model:

- Create a global three-hold model of coarse mesh density (Figures 1, 2, 3)
- Use either bending or membrane element for plates and lumped longitudinal stiffeners as rods.
- A Finer mesh may be included in certain areas to better determine if local detail analysis is necessary
- Applied load should be shifted for those elements without beam or out of plane plate element support.

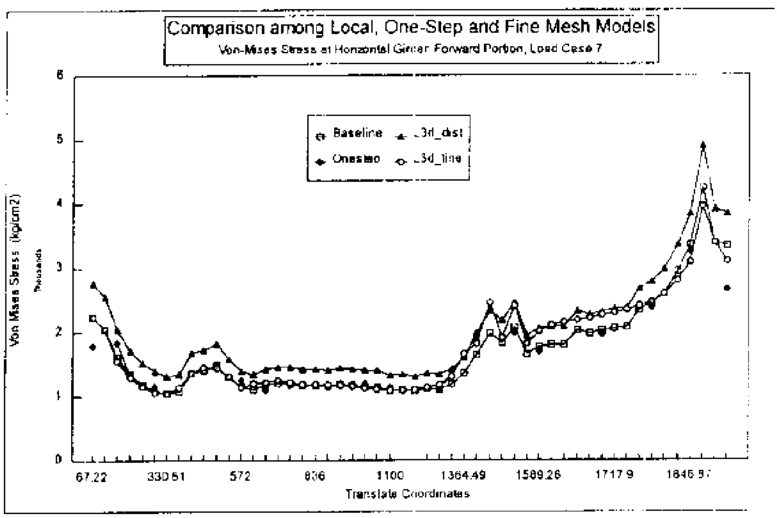

Figure 11. Stress Comparison between One-Step and Fine Mesh Models (Girder)

3D Local Fine Mesh Model:

- Models of principal supporting members should be extended perpendicular to the members of interest to avoid the local boundary effect.
- Line loading or distributed loading is an option for those local models with realistic rotational boundary conditions. Only line load should be used if global model cannot provide realistic nodal rotations.
- Most stiffeners can be omitted except for longitudinal stiffeners and stiffeners close and parallel to the principal direction of stress.
- When using line loading and not rotational boundary conditions, bending plates should be used and longitudinal stiffeners omitted.
- When using distributed loading and rotational boundary conditions, bending plates and longitudinal beam should be used.

Figure 11 shows that the stress comparison of the horizontal girder (HG4) between one-step and fine mesh models for the elements of the inner edge along the line of a-b-c-d-e-f (as shown in Figure 10). The "Baseline" result is from the very fine mesh model, shown in Figure 5. The "One-step" result is from the one-step model, shown in Figure 4. The "L3d_dis" result is from the local 3D fine mesh model, shown in Figure 8, with distributed load and both translational and rotational boundary conditions. The "L3d_line" result is from the local 3D fine mesh model shown in Figure 8 with line load and both translational and rotational boundary conditions. In order to apply the distributed load to the horizontal girder, the local 3D model was extended to HG3 and inner bottom, so that the boundary condition can be considered reliable. It can be seen that using line load for the horizontal girder provides reasonable results.

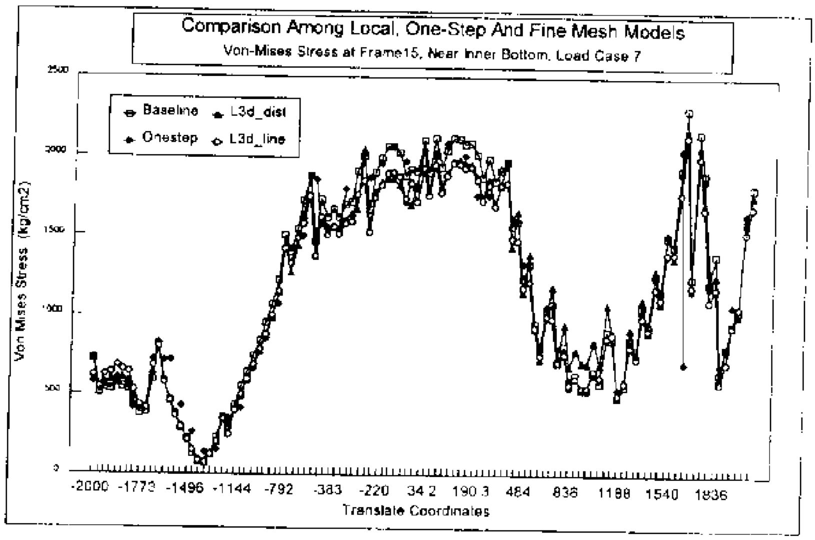

Figure 12. Stress Comparison between One-Step and Fine Mesh Models (Web)

Figure 12 shows the stress comparison for the recommended approach for the transverse web frame between one-step and fine mesh models for the elements near the inner bottom along the line of a-b-c-d-e-f-g-h shown in Figure 9. It can be clearly seen that comparison is fairly good for the recommended approach for transverse web frames.

Summary

To reduce the time required to develop and analyze a highly detailed finite element model, two alternate methods have been presented to simplify the stress analysis of ship structures. In the first method, a two-step approach of a three-hold 3D coarse mesh analysis followed by a series of local 3D analyses can effectively predict stress distributions. In the second approach, a one-step 3D fine mesh of the three-hold model can reduce the need for local 3D analysis. Either technique will arrive at essentially the same stress predictions.

The advantage of the two-step approach is that modeling and analysis time can be reduced dramatically and 3D global model can still provide reliable stress results for hull girder strength evaluation. It also makes iterative design procedure (re-analysis) more feasible as the analyst can modify and rerun global model in a short period of time. For local 3D analysis, the zooming technique can be applied to automatically generate local 3D detail models. The load and boundary displacement can be applied automatically to the local model. The disadvantage of the two-step approach is that many models need to be created and analyzed.

The one-step fine mesh approach reduces the need for further local 3D analysis. When local 3D analysis is required, zooming and refinement procedure is very simple because the structural details and geometry have already been defined in global 3D model. Of course, the disadvantage of the one-step fine mesh approach is that extra time is required for modeling and solution, and more computer resources are required to solve such a large problem. Therefore, this approach makes the iterative design procedure less feasible because small change in mesh detail requires the re-analysis of the entire ship structure. Local 3D models will be required for those principal internal supporting structure details where it is impossible to include a sufficient element density in the three-hold model.

The best practice is to always create the three-hold 3D coarse mesh model to consist of bending plates and beams, whenever possible. To reduce modeling time, rods may be used in place of beams and membrane plates may be used instead of bending plates in three-hold 3D coarse mesh model. When membrane plates and rods are used, nodal rotations will not be computed and will not be available for use as boundary conditions on the local 3D models. This study finds that ignoring nodal rotation in the global 3D analysis will affect the accuracy of the local 3D models. For this reason, more engineering judgement will be required for those global models consisting of something other than bending plates and beams. The local 3D model should consist of longitudinal stiffeners if rotation boundary can be provided from 3D global analysis, Longitudinal beam should be omitted from the local 3D model when rotational boundary conditions are unavailable.

All nodes on the cut boundary should be prescribed boundary displacements computed in the 3D global analysis. When extra nodes are added on the cut boundary due to mesh refinement, then prescribed displacements should be interpolated from neighboring nodes. All other nodes should be loaded with the appropriate cargo, ballast and sea loads. Either line loading (all loads lumped onto the plane of interest) or loading all nodes of the local 3D sub-model is acceptable. If line loading is used, the exclusion of beam stiffeners is a conservative assumption and has little effect on the results of most load cases.

Acknowledgement

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TANK TESTING VS COMPUTATIONAL FLUID DYNAMICS (CFD) IN SHIP DESIGN

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1. Introduction

Computational fluid dynamics (CFD) is playing an increasingly important role as a tool in ship design. The last two decades have witnessed rapid growth in the development of computational algorithms for the simulation of a broad variety of ship flows. Fueled by the advent fast micro-processors, ship flow computer programs are progressively finding their way to desktop PC's and into the toolbox of naval architects.

Tank testing is a necessary step in ship design and this state of affairs is unlikely to be seriously challenged in the near future. Yet, the frequency and extent to which tank testing is likely to be used will be challenged by computational methods which have been properly *verified* - debugged, *validated* - compared to physical results, *accredited* - accepted as valid design tools and *transitioned* - used by people other than their developers. A survey of such methods in various stages of development was presented by Beck, Reed and Rood (1996) [1]. Larsson and Baba (1996) [2] presented a review of the use of viscous CFD in predicting the ship wake and resistance. Recent progress towards the computation of potential flow wave ship interactions is reviewed by Sclavounos (1996) [3].

The present article is not intended to be a survey of ship flow computational methods or of the attributes of their respective solution algorithms. Interested readers should refer to the articles listed above and the references therein. Instead this study will address areas in ship hydrodynamic design where CFD has made considerable inroads. The primary accomplishments and challenges faced by computation will be identified. Finally, emphasis will be placed on the ship flow computational method **SWAN** (Ship Wave ANalysis) developed by the authors and their associates [cf. Sclavounos et. al. (1996) [4]]. Several of its applications in ship design will be discussed.

The paper is organized as follows. A variety of ship flows of interest in design are identified and a general discussion of the successes and challenges faced by tank testing and CFD is carried out. Various types of ship hulls are identified and the performance and use of specific computational methods in their hydrodynamic design is addressed.

2. Ship Wave Pattern

Knowledge of the ship wave pattern via tank testing or CFD is important in ship design in a variety of ways. For example, the accurate prediction of the wake trailing a ship is essential for the evaluation of the ship wave resistance. The ship wake and its signature are essential attributes of modern naval hull forms. Moreover, the wave elevation along the waterline of high-speed vessels may play an important role in the design of the ship waterjet propulsion units.

The ship wave pattern is affected both by viscous and ideal effects. Along most of the ship waterline and away from the ship wake, the ship Kelvin wave pattern may be modeled by assuming that water is an ideal fluid. Near the ship stern and in its wake, vorticity generated within the ship boundary layer, the propulsion mechanism and by the stern geometry plays an important role in defining the ship surface wake.

2.1 Tank Testing

Tank tests are effective in evaluating ship wakes since the wave elevation over the entire free surface may be easily measured by a variety of experimental techniques. The challenge faced by experiments is the scaling of the measured ship wake to full scale, where the high Reynolds number alters appreciably the properties and evolution of the free surface turbulent flow compared to laboratory measurements. The comparison of laboratory and full-scale ship wakes is necessary for the development of better scaling laws.

The measurement of the portion of the ship wave pattern not affected appreciably by viscous effects is very reliable and is widely used to verify and validate CFD methods, discussed next.

2.2 CFD

Computational methods have been successful in predicting the ship wave patterns in regimes where the free surface flow is governed by ideal fluid effects. Several such methods have been developed, the majority solving the linear or nonlinear flow around the ship as if the water was an ideal fluid. A comparison of several such methods (and others which account for viscous effects) with experiments was recently carried out by Ratcliffe (1998).

Near the ship hull and in regimes where viscosity does not play an important role, potential flow solvers and RANS (Reynolds Averaged Navier Stokes) methods can predict the surface wave elevation with very good accuracy. Details of the surface wave steepness require a large number of elements or the use of a nonlinear method. Figure 1 compares measured and predicted values of the surface wave elevation with the linearized **SWAN** method along the Series 60 hull.

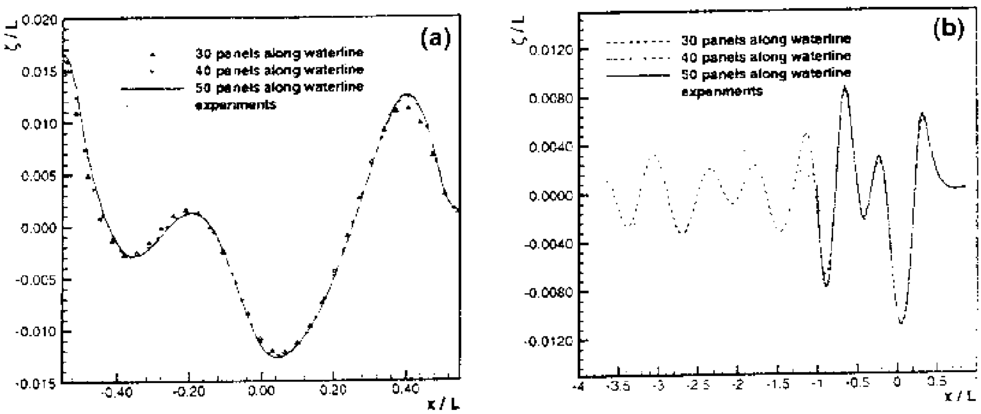

Figure 1: The wave profile along the Series 60 Hull advancing at a Froude number 0.316 along the waterline Figure a) and at a cut along y/L=0.108, Figure b). Results are shown with increasing numbers of panels and are compared to experiments

Near the ship stern and in its wake, the validity of potential flow solvers must be questioned. Their ability to predict ship wake features which are affected appreciably by viscosity and turbulence is limited. For certain hull forms and large scale free surface flow features, such methods often provide useful suggestions which however must be carefully tested before accepted in routine design. A number of methods which account for viscous and free surface effects are under development for this purpose.

Far from the ship and in regimes where viscosity is not important, potential flow methods which solve the free surface flow equations without introducing numerical dissipation have been very successful in predicting the ship Kelvin wake. Figure 2 compares predictions of **SWAN-1** with Kelvin wake measurements by Lindenmuth, Ratcliffe and Reed (1991) for a naval combatant known as the 5415 Hull.

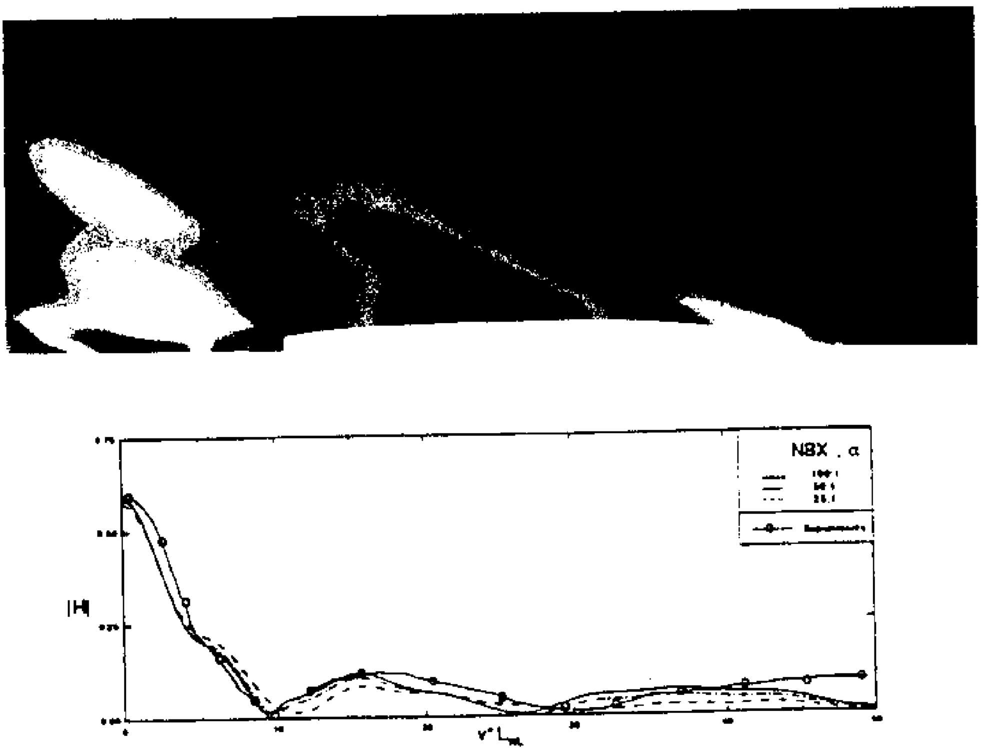

Figure 2: Contour plot of the wave profile around the 5415 hull advancing at a Froude number 0.41. The bottom half of the figure compares the measured and predicted Kelvin wake spectrum as a function of the wavenumber

Several interesting conclusions may be drawn from this comparison, supporting the **SWAN-1** predictions on one hand and pointing to its limitations on the other. The **SWAN-1** Kelvin wake computations may be seen to converge with increasing numbers of panels and to be capable to better resolve flow details as the mesh density increases. Moreover, the measured and predicted Kelvin wake spectra, plotted at the bottom of the figure, are seen to agree well over the small and moderate wavenumber regime. The agreement over the short wavenumber regime is not satisfactory and is attributed to viscous and nonlinear effects arising from the ship wake where free-surface turbulence can no longer be ignored.

Related to the ship wave pattern measurement and prediction, is the evaluation of the ship nominal and effective wake for use to design ship propulsors. The literature on this subject is extensive and this subject will not be addressed in the present article. However, it is worth noting that most of the RANS methods under development for the prediction of the ship wake, are evolutions of methods originally developed for the prediction of ship propeller wakes.

3. Ship Resistance

The evaluation of the resistance of a ship by analytical or computational means remains the Holy Grail of ship hydrodynamics. Since the 1898 Mitchell thin-ship theory and a century of advances in theoretical and computational ship hydrodynamics, the evaluation of the resistance of many vessels with the accuracy demanded by industry is still the purview of tank testing.

However, while modern CFD methods are not capable to predict the ship service speed to within a fraction of a knot, they may offer valuable assistance to the ship designer on how to minimize ship resistance and improve hull form design.

Here, it is necessary to define and discuss the resistance components of conventional and high-performance ship hulls, and identify those that stand to benefit from improved tank testing techniques and CFD methods.

3.1 Frictional Resistance

This is the resistance component obtained by treating the wetted surface of the ship hull as a flat plate and using the ITTC friction Line for the relevant Reynolds number to evaluate the frictional drag. Areas where CFD may improve the prediction of the frictional resistance is in the evaluation of the ship wetted surface which may differ appreciably from its static value for hulls with overhangs at the bow an stern. This is typically the case in sailing yacht design.

The frictional resistance evaluated as defined above, is largely dependent on the Reynolds number and to a far lesser extent on the Froude number. The latter dependence arises from the variation of the ship wetted surface and the influence of the Froude number upon the Form Resistance, discussed below. The frictional resistance using the static wetted surface is often subtracted from the total model resistance measured in tank tests, in order to obtain the remainder, often referred to as the Residuary Resistance.

The contribution of CFD in this process is to better predict the dynamic wetted surface and on certain occasions the influence of wave effects upon the form factor. Both these effects are complex to identify via pure tank testing.

3.2 Residuary Resistance

The simplest definition of the Residuary Resistance, adopted in the present article, is the difference of the total resistance and the flat plate frictional resistance evaluated using the static wetted surface. Under this definition the frictional resistance is purely Reynolds number dependent, with all Froude and some Reynolds number effects transferred to the Residuary Resistance. If the dynamic wetted surface is used, e.g. estimated by a CFD method, some Froude number effects are included in the frictional resistance.

Tank testing, often evaluates the Residuary Resistance as described above, namely using the static wetted surface to determine the frictional component. On certain occasions dynamic effects may be accounted for by sinking and trimming the model to their values at the vessel cruising speed. Thereafter, it is left with the ship designer to identify the various components of the Residuary Resistance, either via further tank testing, e.g. low-Froude number runs to determine the form resistance using Prohska's method, experience or CFD. All these are discussed in more detail below. The primary components of the Residuary Resistance are:

- Wave Resistance
- Form Resistance
- Induced Resistance

3.3 Wave Resistance

The wave resistance is defined as the component of the Residuary Resistance which depends primarily on ideal fluid effects and is therefore Froude number dependent. This is the component of resistance which may be evaluated by standalone potential flow CFD methods. When available via computation, the wave resistance may be of great value to the designer particularly for ship hulls cruising at high speeds.

Identifying with accuracy the wave resistance from a tank measurement is not easy, unless the form and residuary resistance components are known for similar hulls, experience or further tank testing. As discussed below, this may not always be a feasible or inexpensive task.

Therefore, the evaluation of the wave resistance from linear or nonlinear potential flow CFD methods is of great value to ship designers. Several such linearized and some nonlinear methods have been developed and have shown considerable promise in evaluating the wave resistance of cruiser and transom stern ships, as well as sailing yachts [cf. [3],[4]].

A fully nonlinear potential flow solution will generally produce a more accurate prediction of the wave resistance. However, equally important to the selection of a nonlinear wave resistance method, is the development of a robust solution algorithm. Discretization errors must be identified and controlled via systematic convergence tests for a base linearized method, prior to an attempt to include nonlinear effects which are often delicate to model numerically.

Moreover, from the point of a view of the ship designer, it is important to identify the various sources of nonlinearity in the wave resistance of ships. At moderate and high speeds they are:

- Vessel sinkage and trim
- Nonlinear Variation of the Ship Wetted Surface
- Nonlinear Variation of Pressure along the Ship Hull

Several of these effects may be approximated with good accuracy by linearized methods like **SWAN**. The vessel sinkage and trim and the respective wave resistance may be determined from the iterated execution of a linearized CFD method. The same applies to the approximation of the nonlinear variation of the ship wetted surface. Finally, a wave resistance method like **SWAN**, which does not introduce numerical dissipation into the computation of the surface wave profile, may be used to evaluate the wave resistance from a wave cut analysis [cf. Nakos and Sclavounos (1993)]. This technique was pioneered by Eggers, Sharma and Ward (1967) as a very reliable means of identifying the ship wave resistance experimentally.

Later in this section the implementation of the techniques discussed above will be demonstrated with the linearized potential flow CFD method **SWAN** for the evaluation of the Residuary Resistance of ships, including nonlinear effects.

However, the comparison of these **SWAN** CFD predictions with experiments is premature before the two remaining components of resistance are discussed. In ship design, an effort to evaluate the ship wave resistance with a CFD method with high accuracy is often misguided when the Form and Residuary Resistance components are important and often hard to determine through tank testing or via the use of CFD methods.

3.4 Form Resistance

It is common practice in the marine hydrodynamics and ship design literature to define this component of resistance as the remainder when the sum of the Frictional and Wave Resistance as defined above, are subtracted from the total resistance measured in a tank test.

For conventional ships which cruiser sterns, the Form Resistance is often a small yet important component which scales primarily with the Reynolds number. This is the fundamental assumption of Froude's scaling law which is widely practiced with success by the ship design community, especially for ships with conventional hull shapes cruising at moderate speeds.

The precise determination of the Form Resistance, or its form factor, is far from a trivial task either experimentally or by using advanced infinite flow CFD methods. The Form Resistance depends critically on the viscous and turbulent flow features near the ship stern, which are known to vary drastically for various hull forms and stern shapes. Moreover, at high speeds the Form Resistance gains a dependence on the Froude number due to the influence of free surface effects upon the Frictional Resistance (through the variation of the wetted surface) and upon the viscous flow features near the ship stern.

Therefore, the estimation of the Form Resistance via tank testing is often more art than science, particularly when it comes to the scaling of tank measurements of resistance to the full scale vessel. Through experience, experimental facilities have developed empirical methods to accurately determine the Form Resistance for classes of ships or sailing yachts, the full scale performance of which is known. This experience is often translated into a correlation coefficient which when included into the scaling law produces full scale values of the ship resistance or effective horsepower acceptable by industry.

Similar empiricism is frequently present but not widely advertised in CFD methods, particularly when it comes to the selection of the solution algorithm and the choice of the corresponding discretization parameters. It is the authors' view that such empiricism in CFD is justifiable, as long as it is practiced in an open manner. The free surface flows treated by the current CFD methods are complex and the marine hydrodynamics and ship design community stand to both benefit from an open communication on the degree to which empiricism is practiced both in experiments and computation.

3.5 Induced Resistance

The Form Resistance of high-speed vessels with streamlined hulls and transom sterns arises largely from the flow separation around the transom section. Vorticity is generated and shed on the free surface and the ship wake generating a component of drag which may be significant and depends critically on the ship speed and the design of the stern region. Because of the evident analogy to the origins of the induced resistance of three dimensional lifting surfaces, the Form Resistance is for this class of vessels is here referred to as Induced Resistance.

There exists no clear demarcation between the stern shapes for which the fluid mechanics described in the previous paragraph becomes dominant, relative to the fluid mechanics responsible for the more conventional Form Resistance discussed in the previous section. Yet, for the class of high-speed mono or multi-hull vessels with transom sterns the classification of this component as Induced Resistance is more appealing.

It is clear that a portion of the Induced Resistance as defined above, belongs to the Wave Resistance as evaluated by potential flow CFD methods or via wave cut analysis in tank testing. Yet, the significant portion of it which is of viscous origin cannot be accounted for by a linear or nonlinear potential flow solver. This becomes evident from the discrepancy between tank measurements of the total resistance relative to the sum of the Frictional Resistance and the Wave Resistance evaluated by potential flow CFD methods like **SWAN**. This difference, defined here as the Induced Resistance, depends on both viscous and free surface effects and therefore must scale with both the Reynolds and Froude numbers.

Extrapolating the Induced Resistance to full scale remains one of the primary challenges faced by fluid dynamicists, CFD developers and ship designers. By virtue of its complexity, this scaling law will need to draw upon the combined used of tank testing and CFD. Its practical significance is hard to overstate. Several high-speed vessels are under consideration for naval and commercial use and the need exists for their full-scale resistance to be extrapolated from tank testing and computation. In light of the speed and scale of these vessels, progress towards the better determination of their resistance is of undeniable value.

4. Ship Resistance Computations with SWAN

This section presents comparisons between measurements and computations of the Residuary Resistance of various vessels, using the CFD method **SWAN.** The various components of resistance are separated as described in Section 3. Namely, the frictional resistance, evaluated using the ITTC 57 line assuming that the flow is turbulent along the entire ship length, is subtracted from the measured resistance. The wave resistance is determined from the **SWAN-1** (steady-state) or **SWAN-2** (time-domain) potential flow solvers, allowing for the vessel sinkage and trim. In the case of the sailing yachts, the dynamic wetted surface of the yacht has been taken into account both in the evaluation of the Frictional Resistance (increased wetted surface) and the Wave Resistance (elongated ship hull for the same displacement). The treatment of the Form or Induced Resistance is discussed on a case per case basis.

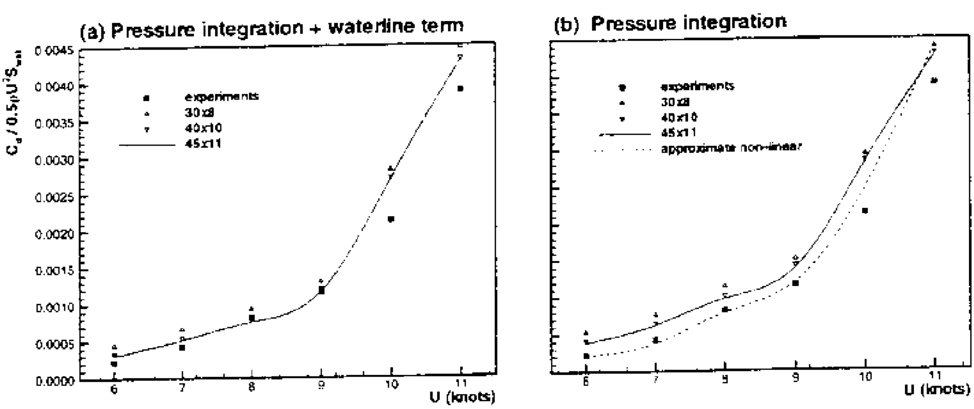

Figure 3: Wave resistance coefficient of an IACC yacht. The convergence of the **SWAN-2** computations with increasing numbers of panels is illustrated for the linearized method (solid line). The approximate account of nonlinear effects (dashed line) arising from the evaluation of the variable wetted surface is seen to improve the wave resistance prediction.

Figure 3 compares the Residuary Resistance of a 1995 America's Cup yacht cruising upright at a Froude number of 0.3. At each speed the yacht is allowed to sink and trim and the resistance is determined at the converged values of these offsets as computed by the potential flow CFD method **SWAN-2** [cf. 3]. At high speeds, the wetted surface of the yacht increases appreciably over its static value due to the hull overhangs near the bow and stem. This apparent lengthening of the wetted length of the yacht has been taken into account in an iterated execution of **SWAN-2** at high Froude numbers leading to an improved prediction of the wave resistance.

The agreement demonstrated in Figure 3 is an example on how a linearized potential flow solver like **SWAN-2** can account for essential nonlinear effects in the wave resistance leading to useful predictions for yacht design. After accounting for the effects of sinkage and trim and the increase of the wetted surface at high Froude numbers, the Form Resistance, was extracted from the tank tests and found to be relatively insensitive to the Froude number for all the computations shown in Figure 3.

Figures 4a and 4b illustrate the steady wave pattern and Residuary Power of the FastShip™ hull, a 770 ft 40knot containership being considered for service across the Atlantic. The FastShip™ is an example of a ship hull with a wide and shallow transom stem and therefore with a significant Induced Resistance component. The Residuary Resistance was evaluated as the sum of

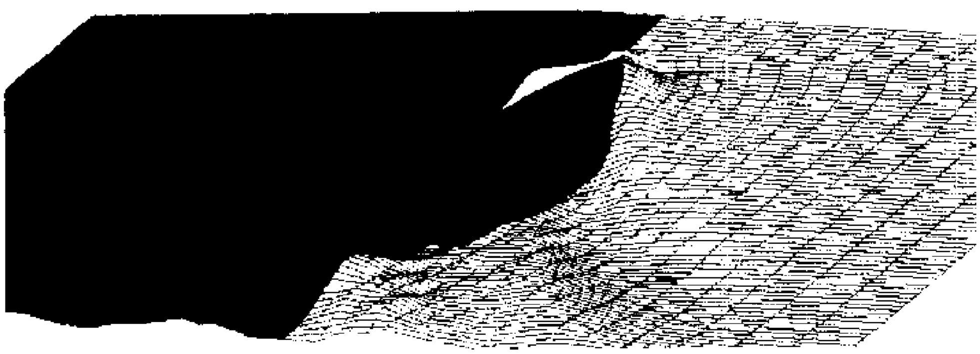

Figure 4a: Steady wave pattern and panel mesh of the FastShip™

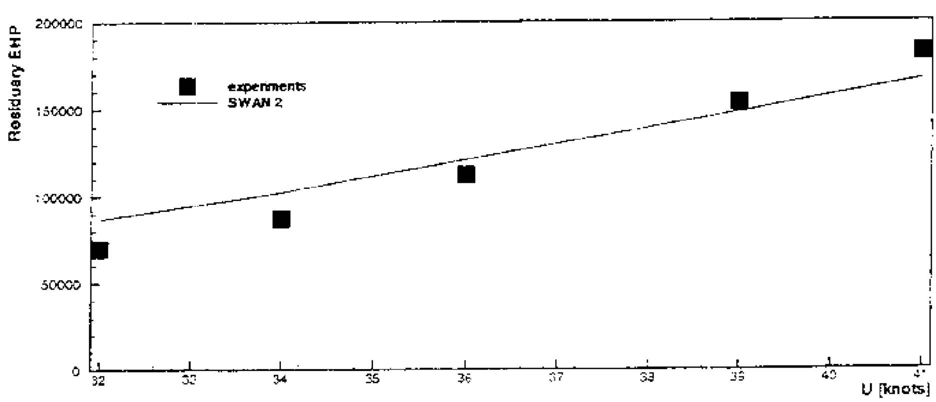

Figure 4b: SWAN-1 Residuary power prediction for the FastShip™

the Wave Resistance computed by **SWAN-1** and an Induced Resistance component that was found to be significant. Its value was determined as a function of the geometry of the transom section, the ship sinkage and trim and correlation with experiments.

This is an example of the synergy between tank testing and CFD in identifying the magnitude of a resistance component that is very complex to estimate from first principles. By subtracting the Wave Resistance as evaluated by **SWAN-1**, it became apparent that the remaining component, the Induced Resistance, was both significant and dependent upon a particular geometrical feature of the ship hull, the shape of her transom section at the sunk and trimmed position. As was the case with the IACC yacht example, the Induced Resistance of the FastShip™ was found to be relatively constant across the speed range shown in Figure 4b.

The same conclusions may be drawn from Figure 5 which compares the Residuary Resistance of a Series 64 hull computed by **SWAN-2** with the experimental measurements carried out by Hugh and Yeh (1964). This evaluation was part of a design study conducted at BMC for a tri-maran vessel intended to cruise at Froude numbers ranging from 0.4 to1.4.

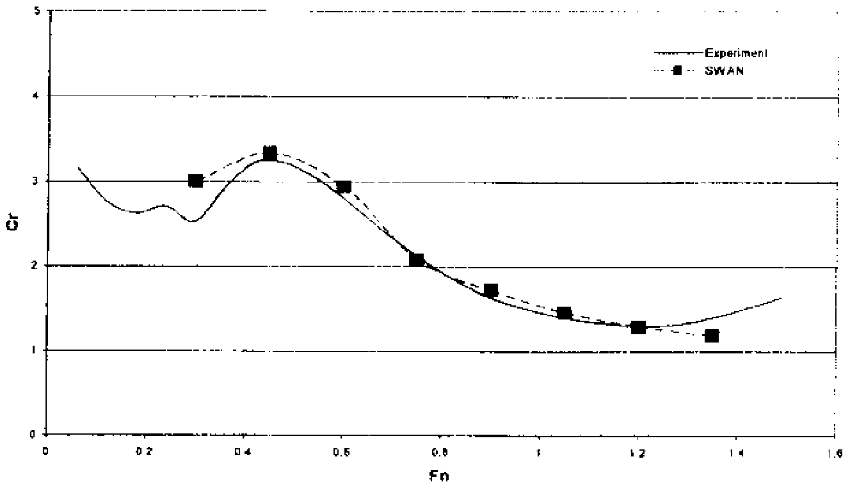

Figure 5: Residuary resistance computations for a Series 64 hull with the **SWAN**-2 method and comparisons with the experimental measurements in the high-Froude-number regime.

Unlike the resistance computations for the FastShip™, the results illustrated in Figure 5 fall in the regime where the total resistance coefficient decreases with increasing speed. In this Froude number range the Wave Resistance is a decreasing portion of the total resistance, when compared to the Frictional and Induced Resistance. It is interesting to note that in the limit of high Froude numbers, the wave resistance tends to zero with the remaining two components (frictional & induced) becoming almost equal in the limit.

The Series 64 study illustrates an important aspect of the total resistance of high-speed vessels, namely, it consists of the frictional component which becomes of increasing importance and of the induced resistance which may be of comparable magnitude. The estimation of its magnitude as well as its scaling to vessels of large size, may be carried out from the combined use of tank testing as well as current and future developments in CFD technologies.

5. Ship Seakeeping

The prediction of the motions and wave induced loads on ships and floating structures in a sea state is one of the unqualified successes of theoretical and computational ship hydrodynamics, as witnessed by the popularity of strip theory and of recent potential flow CFD methods. A comprehensive survey of recent developments in this area may be found in [1].

The primary reason for this state of affairs in ship seakeeping, is the reduced influence of viscous effects on the unsteady forces exerted upon floating structures by ambient waves. An exception is the importance of viscous effects in the determination of the damping mechanism governing the rolling motion of certain ships. There exist other such examples, yet drag models, based on Morison's equation, have proven very reliable. Otherwise, viscosity in seakeeping if far reduced compared to its leading role in the ship resistance problem.

5.1 Tank Testing

Established tank testing techniques exist for the evaluation of the seakeeping properties of a variety of ships. The most common are usually conducted in towing tanks or wave basins equipped with wavemakers capable of generating monochromatic or random wave trains. The standard output from such experiments include the vessel Response Amplitude Operators (RAO's), namely the ratio of the ship-motion/ambient-wave amplitudes in monochromatic waves. The subsequent use of linear system theory, permits the study of the vessel responses in a variety of wave spectra and design conditions.

More specialized seakeeping tank testing techniques involve the measurement of the vessel added-wave resistance, the vessel response in extreme waves and in conditions likely to cause capsizing and the measurement of wave induced impact and structural loads upon models which have been properly instrumented.

A large body of experiments is available. Moreover, our understanding of the basic physics involved in the ship seakeeping problem is at a very advanced state. The same applies to recent CFD methods which are increasingly capable to simulate some of the most complex wave induced effects. Consequently the use of computation is increasingly gaining ground as a reliable and necessary tool for the design of ships designed to withstand severe weather conditions.

5.2 CFD

Strip theory, it still the most widely used analytical/computational method for the evaluation of the seakeeping properties of ships by theoretical means. Its simplicity and effectiveness for many ship forms and wave conditions are two of the reasons. Yet, its limitations can be quite severe and are well documented. Examples are the prediction of the ship motions at high speeds or in following waves, seakeeping prediction for ships with transom sterns, the evaluation of the wave induced structural loads in waves of moderate and large steepness. Finally, the capabilities of strip theory are quite limited when it is used to predict the seakeeping of modern multi-hull vessels where the hydrodynamic interaction between the hulls is of importance in design.

The primary shortcoming of strip theory arises form its approximate two-dimensional treatment of the flow along the ship hull, but in particular near its ends. This limitation was recognized by several researchers in the 60's and 70's but the complexity of the unsteady flow around a realistic ship hull and the lack of powerful computers until the early 80's prevented the emergence of three-dimensional potential flow CFD methods.

This state of affairs started changing rapidly in the mid-80's when several powerful three-dimensional panel methods were developed for the treatment of the seakeeping of stationary structures and ships. A complete account of these developments may be found in [1].

In this article we present examples from the performance and use in design of the **SWAN** CFD method, which has been used extensively of the study of the seakeeping properties of several hull forms. A complete account of the range of applications of the **SWAN** CFD method in ship and offshore platform design is presented in [Sclavounos et.al. (1996)].

Figure 6 illustrates the **SWAN** computations of the heave and pitch RAO's of the FastShip™ hull and their correlation with experiments in waves of moderate steepness.

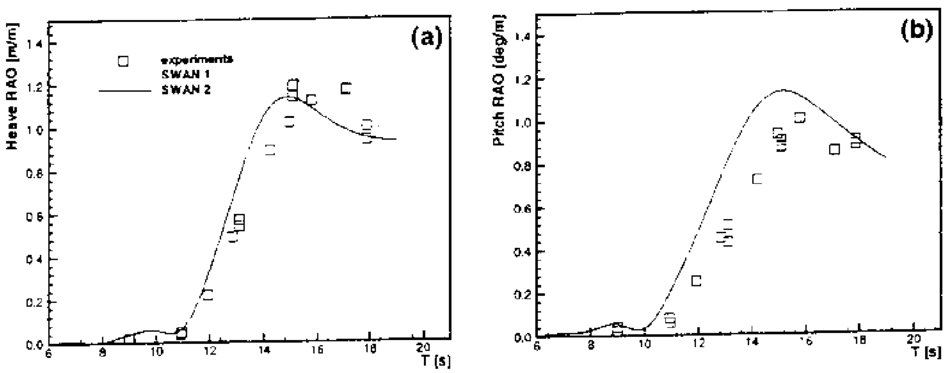

Figure 6: Comparison of the heave and pitch RAO values for the FastShip™ evaluated with the methods **SWAN-1** and **SWAN-2**. Comparisons with experimental measurements shows good agreement.

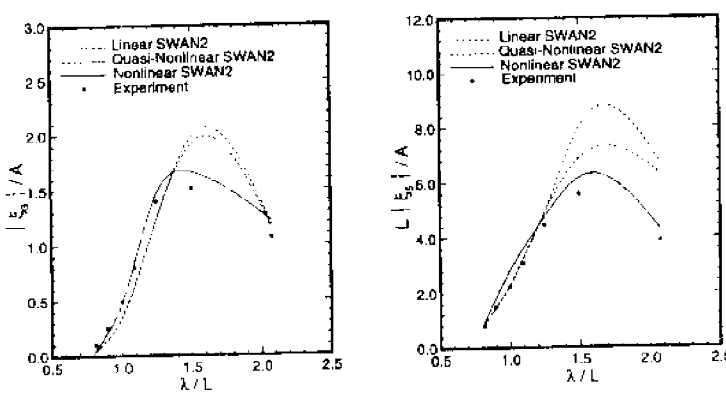

Figure 7: Comparison of the heave and pitch RAO values for the high-speed containership Snowdrift advancing at a Froude number 0.325. Comparisons with experiments shows the superior performance of the nonlinear SWAN predictions over their linear counterparts.

The comparison of the **SWAN** heave and pitch RAO predictions with experiments for a high-speed containership in steep waves is illustrated in Figure 7, where the linear and nonlinear versions of the **SWAN** CFD method are seen to deviate a lot. The nonlinear method is seen to correlate very well with experiments, confirming the validity of a nonlinear potential flow CFD method in modeling the seakeeping of ships in steep waves.

An attractive attribute of a three-dimensional CFD panel method, like **SWAN-2**, is its ability to model complex ship hull geometries. Figure 8 illustrates the steady wave pattern generated by a generic catamaran vessel cruising at three speeds, or at Fr=0.3, 0.55 and 0.80. It is evident from Figure 8 that important interaction effects may persist between the two hulls that a three-dimensional CFD method can model.

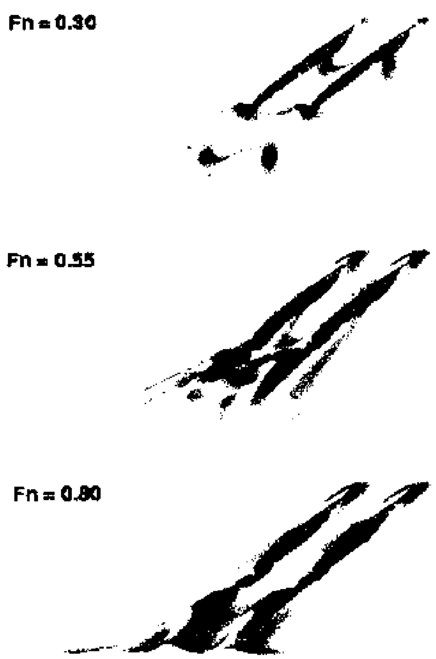

Figure 8: Kelvin wave pattern generated by a catamaran vessel cruising from moderate to high speeds.

The sensitivity of the wave resistance, roll, heave and pitch RAO's on the hull separation to beam ratio is illustrated in Figure 9. The wave resistance predicted by **SWAN-2** may be seen to increase with decreasing separation, indicating destructive interference for this catamaran configuration. The roll RAO is seen to display a drastically different behavior as a function of the wavelength-to-length ratio as the vessel advances at a Froude number 0.8 in beam waves. The hydrodynamic interaction between the hulls also affects the vessel heave and pitch RAO's in head waves. It is evident from Figure 9 that decreasing the hull separation introduces significant interaction effects which tend to decrease the heave and pitch RAO's for smaller separations and to shift their resonance to longer waves (or lower frequencies) as the speed increases from a Fr=0.55 to a Fr=0.8. More details are presented in Kring et. al. (1997).

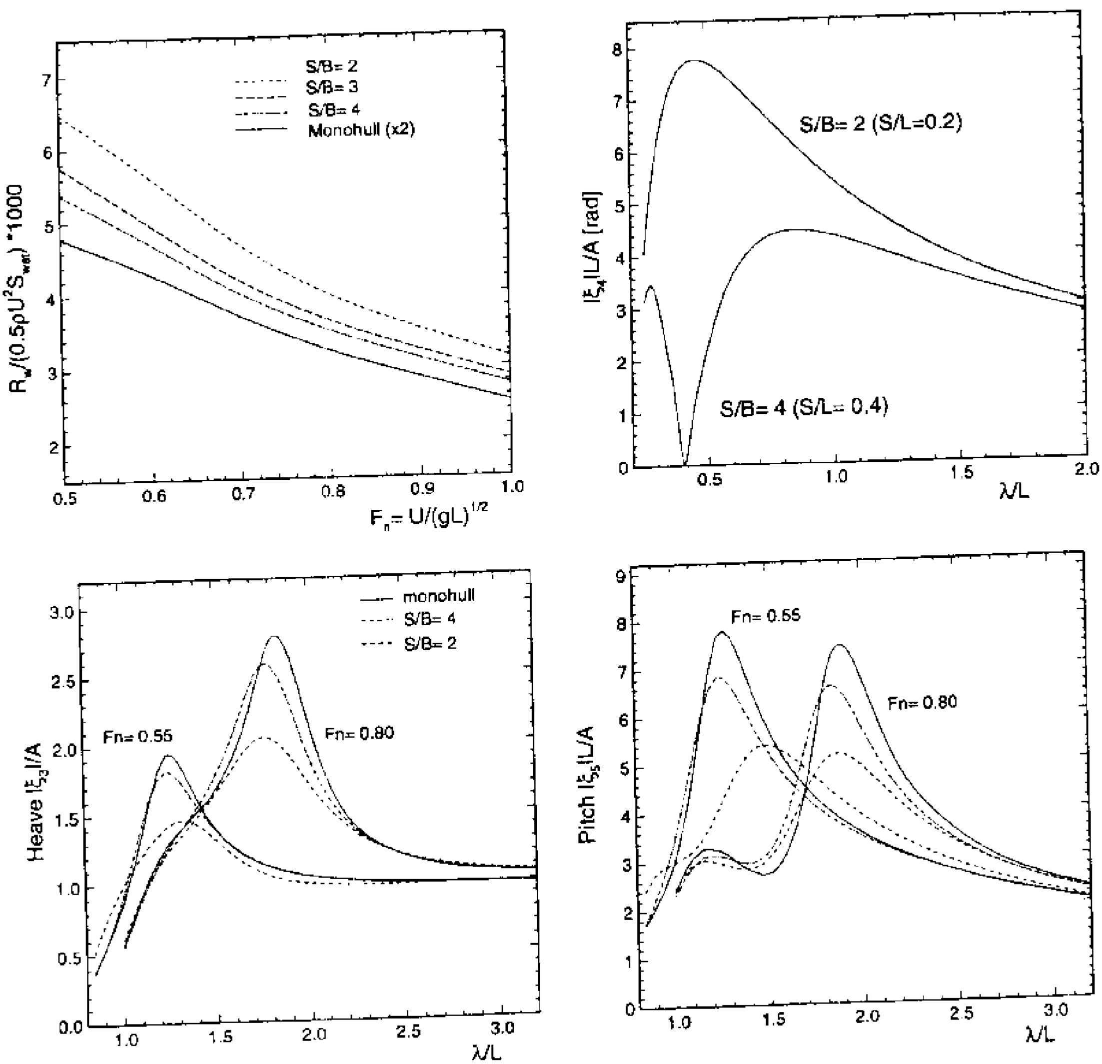

Figure 9a-d: a) Wave resistance coefficient as a function of speed of a catamaran with various demi-hull separation ratios. b) Roll RAO for a catamaran advancing at a Fr=0.8 for two separation ratios. c)-d). Heave and Pitch RAO's for a catamaran at various separation ratios and two speeds.

These computations illustrate the usefulness of a CFD seakeeping method like **SWAN-2** in the design of conventional and modern ship concepts. The accuracy, robustness and efficiency of the method allows the easy evaluation of the ship performance in waves and the study of several attributes of the ship design. This is particularly true for multi-hull vessels considered for leisure or commercial markets. Their seaworthiness is a very attractive design attribute. It may be achieved in a variety of ways, namely the selection of an appropriate hull shape, the use of a single or multiple hulls with optimal spacing for a given displacement or the design of appendages which act to reduce the vessel responses and structural loads in severe weather. In this endeavor, the use of CFD can be an invaluable addition to the toolbox of the ship designer.

6. Conclusion

The article addressed the role of tank testing vs. CFD is ship hydrodynamic design. A review of fluid dynamic issues and widely accepted approximations, practices and trends in tank testing and in the development of CFD methods was carried out. Two areas of ship hydrodynamic design were addressed in some detail a) the evaluation of the ship wake and resistance in calm water and b) the ship seakeeping in waves. In the first area, tank testing plays a central role for the evaluation of the ship wake and resistance. Yet, recent developments in potential and viscous flow CFD are beginning to generate very reliable predictions and trends of value to ship designers.

In ship seakeeping, recent potential flow CFD methods are beginning to show great promise as alternatives to tank testing. The reduced importance of viscous effects and the ability of these methods to treat complex ship hull geometries and configurations increase their value as design tools for the new generation of high-performance vessels for which design databases and experience are both limited.

The relative merits and interaction between tank testing and CFD were underscored by presenting and discussing examples from the application of the potential flow CFD method **SWAN** to several ship and yacht design studies.

7. Acknowledgements

Financial support for the research projects which led to the development of **SWAN** has been provided by the Office of Naval Research (under the direction of Dr. Edwin Rood, Dr. Patrick Purtell and Dr. Art Reed) and Det NorskeVeritas. Several of the results presented in this article have been obtained from design studies carried out by Boston Marine Consulting Inc. for the marine industry.

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FORM PARAMETER APPROACH TO THE DESIGN OF FAIR HULL SHAPES

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Abstract

This paper contributes to the field of preliminary ship design by introducing a new approach to the geometric modeling of hull forms. The approach is based on form parameters, i.e., design relevant descriptors of the envisioned shapes. B-spline curves and surfaces are utilized to mathematically represent a hull's geometry. The modeling process is viewed as an optimization problem in which fairness measures are applied as quality criteria, form parameters are met as equality constraints and B-spline vertices are treated as free variables.

Replacing the currently prevailing design methodology of purely interactive point manipulation, the new parametric approach provides the means for fast and accurate form generation and variation while intrinsically yielding excellent fairness – thus providing the key prerequisites for the systematic improvement of a ship's hydrodynamic performance.

Introduction

In computer aided ship hull design (CASHD) the modeling of a hull's geometry is an undertaking which requires know-how and experience in both naval architecture and geometric modeling – the mathematical representations having largely replaced lines plans drawn with splines and ducks. The prime objective of the hull definition process is to develop a geometric description of the hull form such that

1. all relevant physical and geometrical characteristics – i.e., form parameters like displacement, center of buoyancy, waterplane area, center of flotation, angle of entrance of the design waterline etc. – are met and
2. an acceptable shape quality – often expressed by fairness – is achieved.

Primarily driven by the underlying mathematics, the current methodology of most CASHD systems is based on interactive shape generation. Typically points – e.g. the vertices of a B-spline's defining polygon or polyhedron – need to be manually positioned in three-dimensional space in a highly concerted manner. Conventionally, a naval architect produces an initial shape. He or she then evaluates the hull form in terms of its various derived properties. This means that the current design's actual form parameters are analyzed and compared to desired values and the fairness is judged from curvature plots or simply from a sharp (but subjective) look at the ship lines. The designer then has to modify and assess the geometry repeatedly. Once finished, further changing the geometry either to accommodate new form requirements or to systematically improve the shape to the benefit of, for instance, hydrodynamic performance is a tedious task since fairness has to be brought about by hand, and interactively introduced modifications usually propagate into considerable parts of the hull.

Within this paper a more problem-oriented approach shall be presented which follows the classic naval architect's parametric design technique building on work presented by D.W. Taylor, G. Weinblum and others in the first half of this century. In parametric hull design the prime features of the hull shape are defined via geometric descriptors called form parameters. A ship's geometry is described in terms of longitudinal curves -- so-called basic curves like the sectional area curve and the design waterline. The basic curves are modeled from form parameter input, ideally containing all information needed to produce a hull's shape, see e.g. (Kwik, 1969), (Reed and Nowacki, 1974) (Fuller and Aughey, 1977), (Nowacki, Creutz, Munchmeyer, 1977), (Munchmeyer, Schubert and Nowacki, 1979).

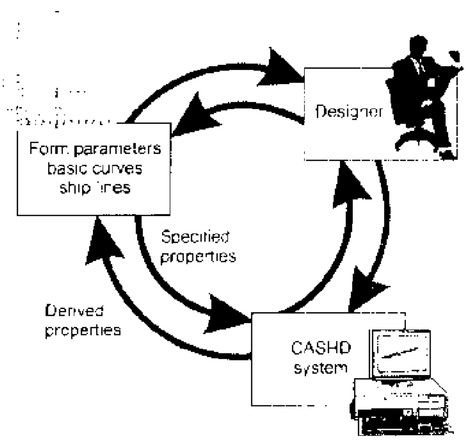

Figure 1. Conventional modeling (clockwise) vs. form parameter design (counterclockwise)

Instead of conventionally generating a shape and deriving its properties afterwards as illustrated by the clockwise process in figure 1, in form parameter design the object's required properties are specified first – i.e., quantified numerically – and then its shape is computed according to these specifications, see counterclockwise process in figure 1. In this way, rather than coping with the underlying mathematics, the naval architect is free to think lines and hull form as expressed by their form parameters. Form parameters can thus be regarded as high-level design elements; they are the vocabulary with which to formulate design ideas.

In the sections to come, the newly developed approach to the parametric design of ship hull forms will be presented. A new method for modeling planar B-spline curves will be described. A generic formulation and several selected examples will be provided. Subsequently, a new skinning method for the generation of fair B-spline surfaces will be proposed. The quality and fairness of the resulting shapes will be demonstrated for the design of a fast monohull, documenting the functionality of all successive design steps. Finally, a brief outlook will be given with respect to the method's applicability to CFD-based hydrodynamic optimization of hull forms within a fully-automatic synthesis model.

Parametric design of ship hull forms

Focusing on bare hulls without appendages as depicted in figure 2, the modeling process is subdivided into three consecutive steps as shown in figure 3, see (Harries, 1998):

1. Parametric design of a suitable set of longitudinal *basic curves*.
2. Parametric modeling of a sufficient set of *design sections* derived from the basic curves.
3. Generation of a small set of *surfaces* which interpolate the design sections.

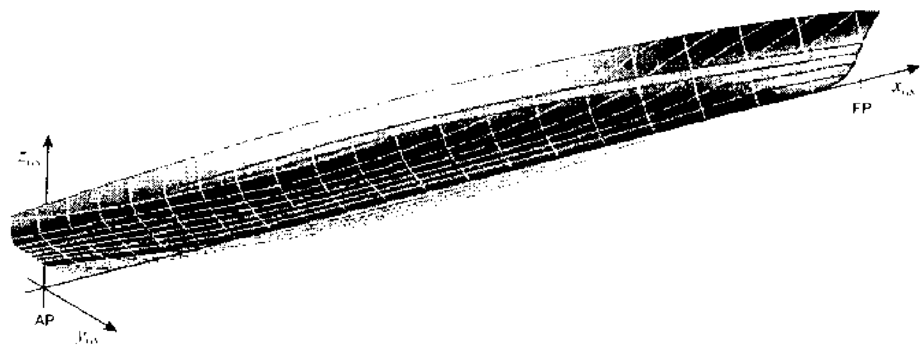

Figure 2. Bare hull without appendages along with global Cartesian coordinate system (y -axis pointing to port) – Form parameter redesigned monohull $D1$

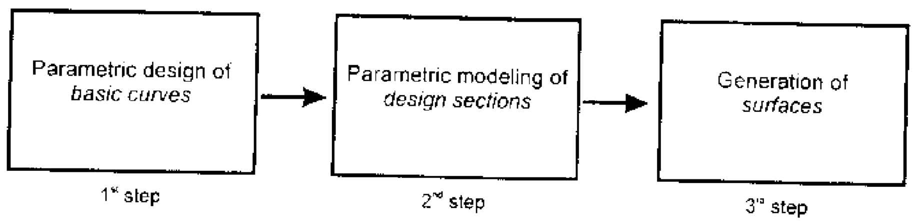

Figure 3. Steps of the shape definition process

Twelve longitudinal, planar curves constitute the set of basic curves currently provided for the design of bare hulls, see tables 1 and 2. Adequate sub-sets can be flexibly combined such that the naval architect is free to choose the set of basic curves depending on his or her particular design task. The basic curves of the fast round-bilge monohull $D1$ - the parent hull of the D-Series by the Berlin Model Basin VWS (Jacobsen and Kracht, 1992) – are shown in figure 4, the curves having been derived from the original offset representation neglecting the small flat keel in $D1$'s middle body. Figure 1 displays the form parameter redesign monohull $D1$ without deadwood and appendages.

Each basic curve is defined by its individual set of form parameters. All curves are thoroughly specified in non-dimensionalized form in (Harries, 1998). Due to its importance for design and hydrodynamics, the length of the design waterline L_{WL} was selected as the universal reference length.

The sectional area curve SAC is depicted as a representative example in figure 5, the abscissa being the non-dimensional longitudinal coordinate $x = x_{GS}/L_{WL}$ and the ordinate being defined by $y = A(x)/A_X$ where A_X is the area of the maximum transverse section at design draft. A set of up to 24 form parameters is utilized for modeling the sectional area curve, containing important quantities like displacement, position of maximum section, centers of buoyancy, slopes at the aft and forward perpendiculars.

Basic curves generally comprise three segments: a curved portion for the run, a straight part in the middle and again a curved portion for the entrance – though the straight part might vanish. Each curved portion is modeled from a flexible set of up to 13 form parameters, representing positional, integral and differential shape requirements as illustrated in figure 6 for the entrance segment of SAC.

A completely curved design section along with its geometric parameters is defined in figure 7. Only the port side is depicted since center line symmetry is assumed. It may be observed from figures

6 and 7 that the very same generic curve parameters are employed for both the segments of basic curves and the design sections. The current set of generic form parameters is presented in table 3.

From the mathematical point of view, the curve generation problem is the same for basic curves and design sections, i.e., planar curves need to be found which simultaneously satisfy a set of chosen form parameters. However, there is a decisive semantic difference between the modeling of the two types of curves: Laying out the basic curves essentially means *preparing the mental plan* for the hull while creating the design sections means *realizing the design idea.*

Table 1. Set of primary basic curves

1	Sectional area curve	SAC
2	Design waterline	DWL
3	Flat of side curve	FOS
4	Center plane curve	CPC
5	Flat of bottom curve	FOB
6	Deck	DEC

Table 2. Set of secondary basic curves

1	Curve of tangent angles at beginning	TAB
2	Curve of tangent angles at end	TAE
3	Curve of curvatures at beginning	CAB
4	Curve of curvatures at end	CAE
5	Curve of vertical moments of sectional area	VMS
6	Curve of lateral moments of sectional area	LMS

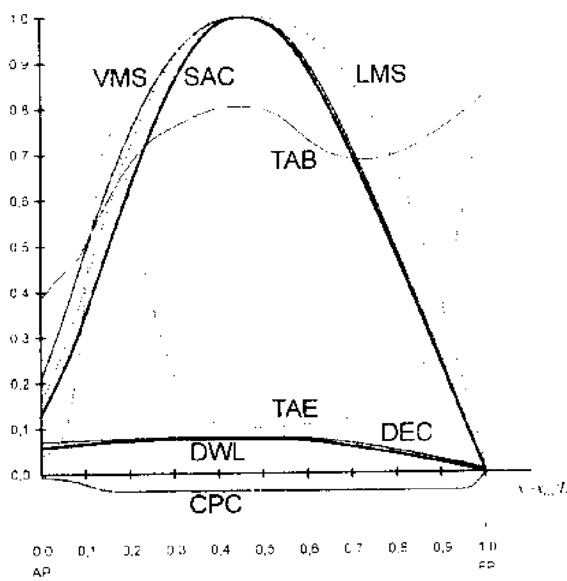

Figure 4. Basic curves of monohull *D1* derived from original geometry – The monohull does not feature FOS and FOB; CAB and CAE are omitted

Parametric design of planar curves

B-splines

Among the many available mathematical techniques the B-splines are outstanding due to their many advantageous features like local shape control, convex hull property and invariance under coordinate system transformation. Shapes with axis-parallel portions and surfaces that are curved in various directions can be easily handled and, consequently, most state of the art modeling systems support the B-spline technique.

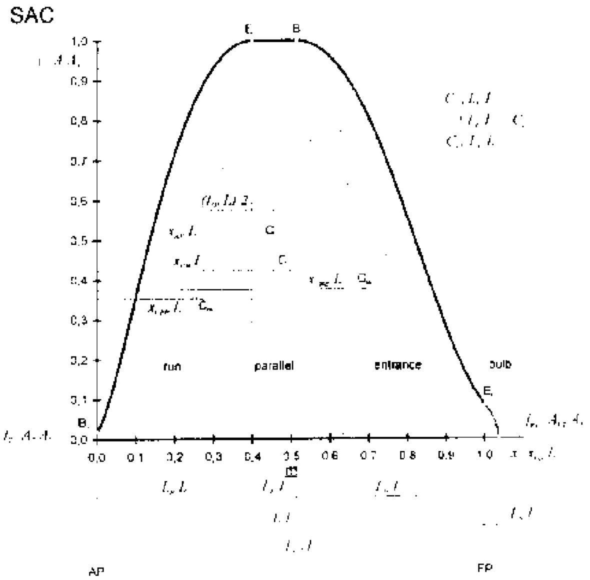

Figure 5. Definition of a generic sectional area curve – Example SAC for a container carrier

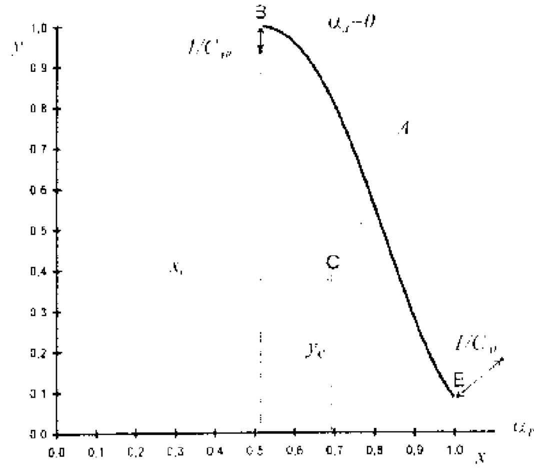

Figure 6. Form parameters for planar curve design illustrated for entrance segment of SAC

B-splines have been the subject of numerous publications - see e.g. (Rogers and Adams, 1990), and (Nowacki, Bloor and Oleksiewicz, 1995) – and shall be discussed here only as needed to understand the new parametric design principles and to get acquainted with the nomenclature used.

A B-spline curve is defined as a piecewise continuous curve which results from the linear superposition of m control points, the so-called vertices of the defining polygon

$$\vec{V}_i = \begin{pmatrix} x_i \\ y_i \end{pmatrix}, \tag{1}$$

multiplied by their corresponding blending functions $N_{ik}(t)$, the so-called basis splines. It is a parametric curve (here in two-dimensional space)

$$\vec{Q}(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \sum_{i=0}^{m-1} \vec{V}_i \cdot N_{ik}(t), \quad m \geq k \tag{2}$$

where the curve parameter varies between a lower and an upper bound, often $0 \leq t \leq 1$, determining the beginning and the end of the curve. The basis splines $N_{ik}(t)$ are ordinary polynomials of order k and may be expressed by the recursive formulae of de Boor, Cox and Mansfield, see e.g. (Nowacki, Bloor and Oleksiewicz, 1995). A knot vector forms an integral part of the B-spline definition. It specifies the parameterization of the basis and, hence, directly influences the properties of the curve. Accordingly, the knot vector decides on the classification of B-splines.

For the parametric design problem open uniform B-spline curves (UBS) were selected for several reasons: Open B-spline curves interpolate the first and last vertex of their defining polygon which is known as the end point interpolation property. At these end points the open B-spline curve is tangential to its polygon's first and last segment, known as the end tangency property. Uniform knot vectors are the convenient choice unless the extra freedom of non-uniform knot spacing is needed.

Table 3. Set of generic form parameters for planar curve design

	Form parameter		Mathematical description	Constraint
1	Position at beginning B	x_B	$x_B = x\vert_{t=0}$	h_1
2		y_B	$y_B = y\vert_{t=0}$	h_2
3	Position at end E	x_E	$x_E = x\vert_{t=1}$	h_3
4		y_E	$y_E = y\vert_{t=1}$	h_4
5	Tangent angle at beginning B	α_B	for open B spline directly via $\bar{V}_0\bar{V}_1$	h_5
6	Tangent angle at end E	α_E	for open B-spline directly via $\bar{V}_{m-2}\bar{V}_{m-1}$	h_6
7	Curvature at beginning B	C_{AB}	$C_{AB} = \frac{x'_B y''_B - x''_B y'_B}{\left(x'^2_B + y'^2_B\right)^{\frac{3}{2}}}$ with $x' = \frac{d}{dt}x(t)$, etc.	h_7
8	Curvature at end E	C_{AE}	$C_{AE} = \frac{x'_E y''_E - x''_E y'_E}{\left(x'^2_E + y'^2_E\right)^{\frac{3}{2}}}$	h_8
9	Area between curve and x-axis	A	$A = \frac{1}{2}\left[\int_{t_B}^{t_E}(yx' - xy')dt + y_E x_E - y_B x_B\right]$	h_9
10	Centroid of area (first order moment)	x_C	$x_C A = M_y = \frac{1}{3}\left[\int_{t_B}^{t_E}(yx' - xy')x\,dt + y_E x_E^2 - y_B x_B^2\right]$	h_{10}
11		y_C	$y_C A = M_x = \frac{1}{3}\left[\int_{t_B}^{t_E}(yx' - xy')y\,dt + \frac{1}{2}y_E^2 x_E - \frac{1}{2}y_B^2 x_B\right]$	h_{11}
12	Interpolation of an intermediate point I	x_I	$x_I = x\vert_{t=t_I}$	h_{12}
13		y_I	$y_I = y\vert_{t=t_I}$	h_{13}

Mathematical model for form parametric design of planar curves

Conventionally, a B-spline's vertices $\bar{V}_i$ are positioned within a highly interactive process as already discussed. The designer is able to anticipate the approximate shape of the curve from the defining polygon. Yet, so as to obtain the desired geometry the control points must be cautiously repositioned by hand. Simultaneously fulfilling several form parameters as specified in table 3 is extremely time-consuming (if not impossible) to achieve manually.

The modeling problem pursued here therefore rather reads: Find an open B-spline curve of given order k, number of vertices m and specified knot vector such that a flexible set of selected form parameters is accurately met. In addition the resulting curve also needs to display good shape quality which means that the curve ought to be fair.

Apparently, a computational model has to be employed to solve this problem. Following an earlier work for Bézier curves presented by (Nowacki, Liu and Lü, 1990), fairness measures can be successfully utilized as problem-oriented criteria in whose terms the quality of a curve may be quantified. Parametric fairness criteria E_n of planar curves are defined by

$$E_n = \int_{t_B}^{t_E}\left\{\left(\frac{d^n x}{dt^n}\right)^2 + \left(\frac{d^n y}{dt^n}\right)^2\right\} dt \tag{3}$$

with $n = 1, 2, 3, \ldots$. Employing these fairness criteria as measure of merit and selecting some or all of the form parameters given in table 3, parametric curve design can be viewed as an equality constrained optimization problem: Determine the coordinates of the unknown vertices $\vec{V}_i$ of the B-spline curve $\vec{Q}(t)$ by minimizing the functional

$$F = e_1 E_1 + e_2 E_2 + e_3 E_3 \stackrel{!}{=} Min. \tag{4}$$

subject to all or several of the following equality constraints

$$\begin{aligned}
&h_1 = x_0 - x_{B_{given}} = 0, && h_2 = y_0 - y_{B_{given}} = 0, \\
&h_3 = x_{m-1} - x_{E_{given}} = 0, && h_4 = y_{m-1} - y_{E_{given}} = 0, \\
&h_5 = \alpha_{B_{actual}} - \alpha_{B_{given}} = 0, && h_6 = \alpha_{E_{actual}} - \alpha_{E_{given}} = 0, \\
&h_7 = C_{AB_{actual}} - C_{AB_{given}} = 0, && h_8 = C_{AE_{actual}} - C_{AE_{given}} = 0, \\
&h_9 = A_{actual} - A_{given} = 0, && \\
&h_{10} = M_{x_{actual}} - x_{C_{given}} \cdot A_{given} = 0, && h_{11} = M_{x_{actual}} - y_{C_{given}} \cdot A_{given} = 0, \\
&h_{12} = x(t_{I_{given}}) - x_{I_{given}} = 0, && h_{13} = y(t_{I_{given}}) - y_{I_{given}} = 0.
\end{aligned} \tag{5}$$

The above equality constraints h_j correspond to the form parameters summarized in table 3 and illustrated in figures 6 and 7. Table 3 also gives closed form expressions for computing the area A between a parametric curve $\vec{Q}(t)$ and the x-axis as well as the area's first order moments. The different fairness criteria in equation (4) can be selected and prioritized by means of their respective weighting factors e_1, e_2 and e_3 as will be discussed shortly, see figure 8.

The coordinates of the first and last vertex may be readily computed from the simple equality constraints h_1 to h_4, utilizing the B-spline's end point interpolation property. Further making use of the B-spline's end tangency property, constraints h_5 to h_6 for the tangent angles at both ends may be incorporated via

$$\vec{V}_1 = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + x_{\alpha_B} \cdot \begin{pmatrix} \cos\alpha_B \\ \sin\alpha_B \end{pmatrix}, \qquad \vec{V}_{m-2} = \begin{pmatrix} x_{m-2} \\ y_{m-2} \end{pmatrix} = \begin{pmatrix} x_{m-1} \\ y_{m-1} \end{pmatrix} - x_{\alpha_E} \cdot \begin{pmatrix} \cos\alpha_E \\ \sin\alpha_E \end{pmatrix}, \tag{6}$$

where x_{α_B} and x_{α_E} are the unknown distances between the first two and the last two vertices, respectively.

By employing Lagrange multipliers $\lambda_j \neq 0$ for the remaining equality constraints h_7 to h_{13} an *un*constrained minimization problem and hence free variational problem can be established:

$$F^* = F + \sum_{j \in [7,13]} \lambda_j h_j \stackrel{!}{=} Min. \tag{7}$$

whose unknowns are the coordinates of the B-spline's free vertices and the Lagrange multipliers for all incorporated form parameters. Presuming an unbounded feasible domain, the first order necessary condition for a local extremum is

$$\nabla F^* \stackrel{!}{=} \vec{0}, \tag{8}$$

i.e., the gradient of the functional equals the null vector. This leads to an equation system which, in general, is non-linear and needs to be solved numerically. The Newton-Raphson algorithm was used as a standard procedure from (Press et al., 1992). It is important to note, however, that both convergence and outcome depend on a reasonable initial guess for the vertex coordinates to be computed, see (Harries, 1998) for an elaborate discussion.

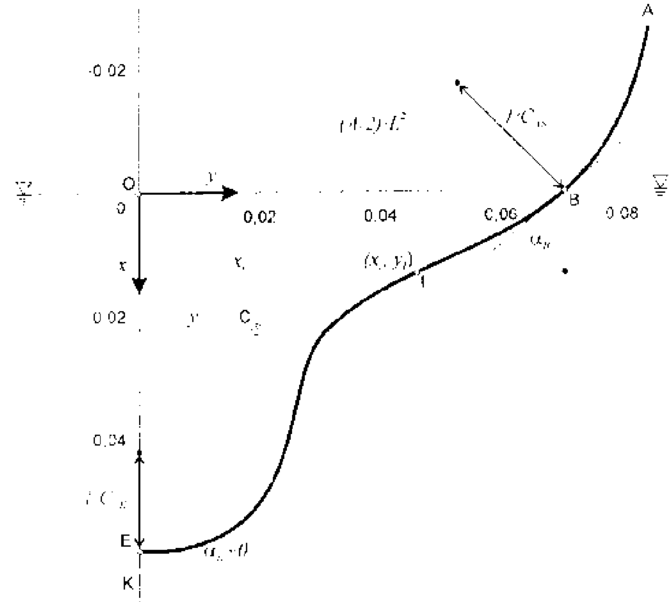

Figure 7. Form parameters for a generic design section – Example aft section of a container carrier

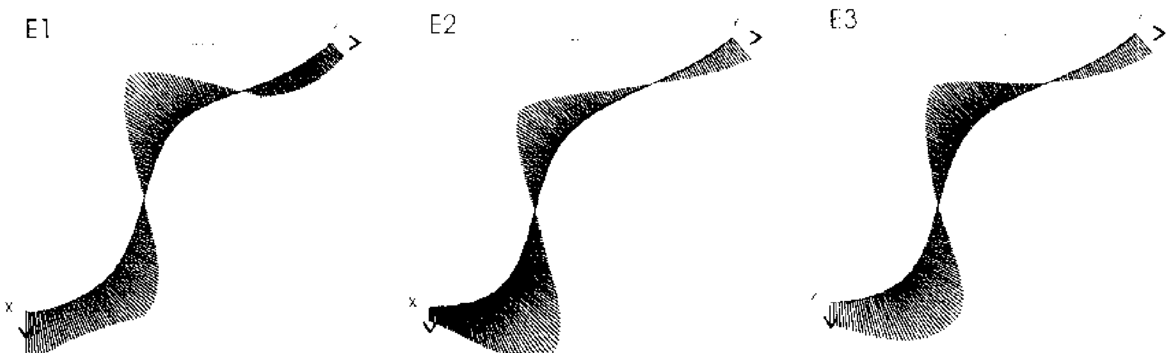

Figure 8. Influence of fairness measures – Form parameter designed aft section of a container carrier where $(x_B, y_B) = (0.0, 0.0699)$, $(x_E, y_E) = (0.0610, 0.0)$, $\alpha_B = -50°$, $\alpha_E = -90°$, $A/2 = 0.002$, $(x_C, y_C) = (0.0227, 0.0201)$

In order to establish an under-determined optimization problem – in order to gain enough leeway for fairing – the number of free variables, here the B-spline vertex components, must be greater than the number of constraints. The relationship between a specific curve and its form parameters is obtained by computing a minimum of the selected measure of merit F^*.

If all thirteen scalar form parameters are to be accommodated at the same time, the planar B-spline curve has to comprise at least seven vertices, amounting to fourteen free variables. The curve acquires a higher degree of freedom, however, if more vertices are provided. Nevertheless, all free vertex coordinates have to be computed within the optimization process by means of solving a non-linear equation system. Hence, a compromise between flexibility and computational effort needs to be found. For the modeling of planar ship lines – design sections, run and entrance segments of the basic curves – about eight vertices are considered reasonable. Choosing a cubic basis, local shape control is already provided with eight vertices since no single vertex influences the entire curve. A cubic B-spline also is twice-differentiable at its inner knots and therefore curvature continuous – a favorable characteristic. Consequently, a cubic open and uniform B-spline curve with eight vertices is a common and possibly standard choice within the form parameter modeling approach.

Example curves

The applicability of the optimization approach to the parametric design of planar curves shall be demonstrated by three representative examples.

Figure 8 displays the underwater part of a container carrier's aft section which was fully designed from form parameter input – see form parameter data in the caption of figure 8 as well as the illustration in figure 7. Three different curves are shown which were computed using the criteria E_1 (spring measure), E_2 (bending measure) and E_3 (jerk measure) separately. Each curve is a cubic open B-spline with uniform knot vector and eight control points. Curvature porcupines are provided to document the excellent fairness resulting from the optimizations. The porcupines also emphasize differences in the outcome. As may be noted from the slightly more pronounced changes in curvature at the inner knots for the E_1 optimized curve, the spring measure E_1 tends to yield slightly tighter curves than the other two fairness criteria. Minimizing only the jerk measure E_3 produces the smoothest curve. Naturally, the fairness criteria can be combined in accordance with equation (4), the resulting curve then being dependent on the selected weighting factors.

The second example is concerned with sectional design for the fast round-bilge monohull *D1* which was already introduced above. The three exemplary sections shown in figure 9 are the entrance section at $x = 0.95$, the maximum section at $x = 0.45$ and the transom stern at $x = 0.0$. The sections are representative to the distinct regions of the hull. The form parameters used for the modeling are summarized in table 4, those that were included in the optimization given on white background.

Again open uniform cubic B-splines with eight control points were used. The curves were optimized with respect to the E_2 criterion. Figure 9 depicts the three curves along with their vertices. The homogeneity of the control point distribution would be difficult to achieve in a manual design process. The first and last three control points, respectively, lie on straight lines for enforced zero curvatures at the ends.

The final example for curve design presents the modeling of three alternative sectional area curves for the monohull *D1*, see figure 10. Each sectional area curve comprises two B-splines for the run and the entrance, the two segments being merged at the position of maximum sectional area A_X at $x = 0.45$. While maintaining displacement, positional and tangency conditions, the longitudinal center of buoyancy was shifted two percent forward and one percent aft, respectively. The thick line is the B-spline representation of the original *SAC* with $x_{CB} = 0.475$, the thin line shows the B-spline curves for the new *SAC* with $x_{CB} = 0.495$ while the dashed line is the *SAC* with $x_{CB} = 0.465$; the B-splines' corresponding vertices are displayed too (circles).

Table 4. Sets of form parameters for modeling the entrance, maximum and aft section of monohull *D1*

	Form parameter		Data	Section		
				Entrance	Maximum	Transom
1	Position at beginning	x_B		0.0	0.0	0.0
2		y_B	$\frac{B/2}{T}$	0.0109	[illegible]	0.0568
3	Position at end	x_E	$\frac{x}{T}$	0.04	0.04	0.0071
4		y_E		0.0	0.0	0.0
5	Tangent angle at beginning	α_B		11.5°	-9.8	45.8°
6	Tangent angle at end	α_E		-80.4°	80.4°	-87.0°
7	Curvature at beginning	C_B	$C_B \cdot L$	18.3	0.0	-137.4
8	Curvature at end	C_E	$C_E \cdot L$	-50.7	0.0	0.0
9	Area between curve and x-axis	A	$\frac{A/2}{T^2}$	0.000282	[illegible]	0.00129
10	Centroid of area	x_c	$\frac{x}{T}$	0.01590	[illegible]	0.00280
11		y_c	$\frac{y}{T}$	0.00399	[illegible]	0.02357

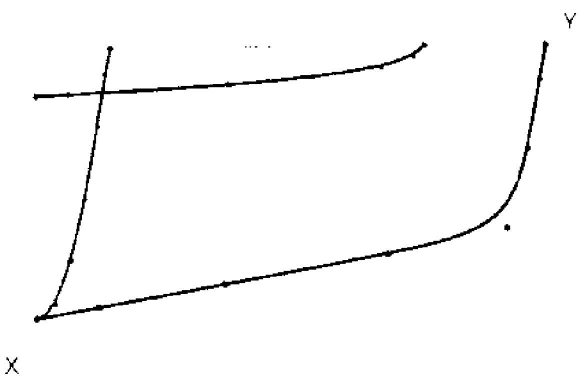

Figure 9. B-spline curves and their vertices (dots) for underwater part of entrance, maximum and aft section of monohull *D1*

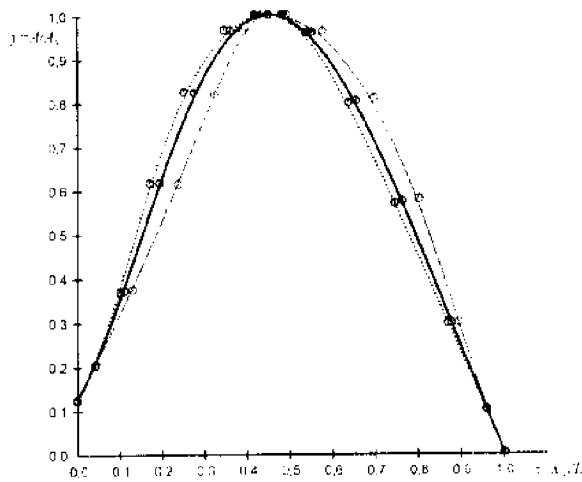

Figure 10. Variation of *SAC* for monohull *D1* by shifting the longitudinal center of buoyancy – Higher level multi-segment B-spline curves

All B-spline curves are cubic and comprise eight vertices. The E_2 criterion was selected as the sole measure of merit. Instead of optimizing the two B-spline curves of each *SAC* separately, the curves are combined to a higher level multi-segment curve to be optimized as a whole. Similarly, all other basic curves are also treated as multi-segment curves where the entrance, straight middle (if present) and run segment are handled in a concerted manner, see (Harries and Abt, 1999) for details.

The *SAC* variation example nicely demonstrates that form parameters can be selected and changed as needed without affecting any other form parameter. Within certain limits form parameters can be modified and controlled independently (Harries, 1998).

Surface generation

Fair skinning interpolation

Within the parametric approach the process of designing a vessel is subdivided into three consecutive steps, thus reducing the complexity of free-form surface design to the level of curve modeling – see figure 3. While in the first two steps planar curves – the basic curves defining the desired shape and the design sections fixing the actual geometry – are modeled from form parameters as discussed above, a surface representation is produced in the third step by means of a new technique which shall be presented below.

An excellent procedure for establishing a mathematically closed surface representation from an ordered set of curves is the skinning algorithm as introduced by (Woodward, 1986 and 1988). It produces a B-spline surface by interpolating a set of transverse curves – the so-called skin curves, here a set of q design sections $\vec{Q}_d\,(u)$ parametrically generated in step 2, see figure 3. Skinning's basic idea stems from lofting. However, the blending is done with respect to the control polygons of the skin curves rather than with respect to the skin curves themselves. A new set of so-called longitudinal B-spline curves is generated such that the vertices of the transverse B-spline curves are interpolated at pre-selected parameter values. The vertices of the longitudinal curves are then employed as the defining polyhedron of a B-spline surface which contains the skin curves as iso-parameter lines.

Let

$$\vec{F}\,(u,v)=\begin{pmatrix} x\,(u,v) \\ y\,(u,v) \\ z\,(u,v) \end{pmatrix}=\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}\vec{P}_{ij}\cdot N_{jl}\,(v)\cdot N_{ik}\,(u) \tag{9}$$

denote the B-spline surface to be computed, $\vec{P}_{ij}$ being its yet unknown control points. Since the design sections $\vec{Q}_d\,(u)$ are to be interpolated by $\vec{F}\,(u,v)$, m rows of vertices, order k and the knot vector used for sectional design are readily chosen for the surface's transverse direction u. For its longitudinal direction v one may use n columns of vertices, order l and a different knot vector.

The interpolating condition reads

$$\vec{F}\,(u,v_d)=\sum_{i=0}^{m-1}\left(\sum_{j=0}^{n-1}\vec{P}_{ij}\cdot N_{jl}\,(v_d)\right)\cdot N_{ik}\,(u)\overset{!}{=}\sum_{i=0}^{m-1}\vec{V}_{i_d}\cdot N_{ik}\,(u)=\vec{Q}_d\,(u) \tag{10}$$

which has to be fulfilled at selected parameter values $v_d = const.$ with $d=0,\dots,q-1$. Equation (10) is known as the skinning condition. Equating coefficients we conclude that for each row $i=0,\dots,m-1$ the relation

$$\sum_{j=0}^{n-1}\vec{P}_{ij}\cdot N_{jl}\,(v_d)\overset{!}{=}\vec{V}_{i_d}=\begin{pmatrix} x_{i_d} \\ y_{i_d} \\ z_{i_d} \end{pmatrix} \tag{11}$$

must hold for all parameter values u with $d=0,\dots,q-1$. The surface generation problem can therefore be broken down to determining m longitudinal B-spline curves

$$\vec{L}_i\,(v)=\sum_{j=0}^{n-1}\vec{P}_{ij}\cdot N_{jl}\,(v)\,. \tag{12}$$

each with n unknown vertices $\bar{P}_{ij}$ where $i = const.$, such that the q related vertices $\bar{V}_{ij}$ of all skin curves are interpolated at $v_0, v_1, \ldots, v_{q-2}$ and v_{q-1}, respectively. The $m \cdot n$ resulting vertices $\bar{P}_{ij}$ of all longitudinal B-spline curves $\bar{L}_i(v)$ then make up the polyhedron of the skinning surface $\bar{F}(u,v)$.

Traditional skinning algorithms solve the linear equation systems set up from equation (11) separately for each Cartesian component and row by row, see e.g. (Nowacki, Bloor and Oleksiewicz, 1995). Usually the parameter values v_d at which the interpolations shall take place are chosen to coincide with the B-splines' knots, in this way unfavorably preempting the surface's longitudinal parameterization unless the skin curves happen to be ordered more or less equidistantly.

Alternatively, fairness criteria may be utilized for computing the longitudinal curves $\bar{L}_i(v)$ by extending the proposed optimization technique for planar curve design to the modeling of space curves. The interpolation problem then becomes: Find a longitudinal B-spline curve $\bar{L}_i(v)$ such that a three-dimensional parametric fairness criterion is minimized, say

$$E_{2_i} = \int_{v_0}^{v_f} \left\{ \left(\frac{d^2 x_i}{dv^2}\right)^2 + \left(\frac{d^2 y_i}{dv^2}\right)^2 + \left(\frac{d^2 z_i}{dv^2}\right)^2 \right\} dv \qquad (13)$$

while the $(3 \cdot (q-2))$ equality constraints

$$h_{x_{id}} = x_i(v_d) - x_{id} = 0,\ h_{y_{id}} = y_i(v_d) - y_{id} = 0,\ h_{z_{id}} = z_i(v_d) - z_{id} = 0, \qquad (14)$$

for all $d = 1, \ldots, q-2$, are *simultaneously* fulfilled at freely selected parameter values v_d. The determination of the first vertex $(d = 0)$ and last vertex $(d = q-1)$ is trivial, since the end point interpolation property can be put to use. The other vertices $\bar{P}_{ij}$ of all longitudinal B-spline *space* curves are computed numerically for each row $i = const.$ just like the vertices of the parameter designed *planar* B-spline curves, i.e., by means of optimization.

Despite higher computational effort, this new skinning approach has several advantages over its traditional counterpart: The longitudinal number of vertices n becomes independent of the number of skin curves q as long as $n > q$ to ensure leeway for optimization. The longitudinal B-spline curves become inherently fair which has an indirect fairing effect on the skinning surface; the approach was consequently called *fair* skinning. No additional information – for instance end conditions – need to be provided and the longitudinal parameterization of the surface can be chosen as desired, e.g. uniform.

Example Surfaces

The various steps of the skinning interpolation are illustrated in figure 11, displaying the surface generation for the underwater portion of the fast round-bilge monohull *D1*. Ten design sections plus a bow contour were form parameter designed as cubic B-spline curves, making up the set of skin curves shown in picture 1. For each B-spline curve a uniform knot vector and eight vertices were used. The defining polygons of all skin curves are shown in picture 2. Eight longitudinal cubic B-spline curves with uniform knot vectors were computed such that the three-dimensional E_2 criterion was minimized and the vertices of the skin curves were interpolated, see picture 3. A total of 15 vertices was chosen for each longitudinal curve, the defining polygons are displayed in picture 4. The defining polyhedron of the resulting bi-cubic B-spline surface is illustrated in picture 5, the vertices of the B-spline surface being the very same as those of the longitudinal curves by premise. Isolines of the resulting B-spline surface are presented in figure 12.

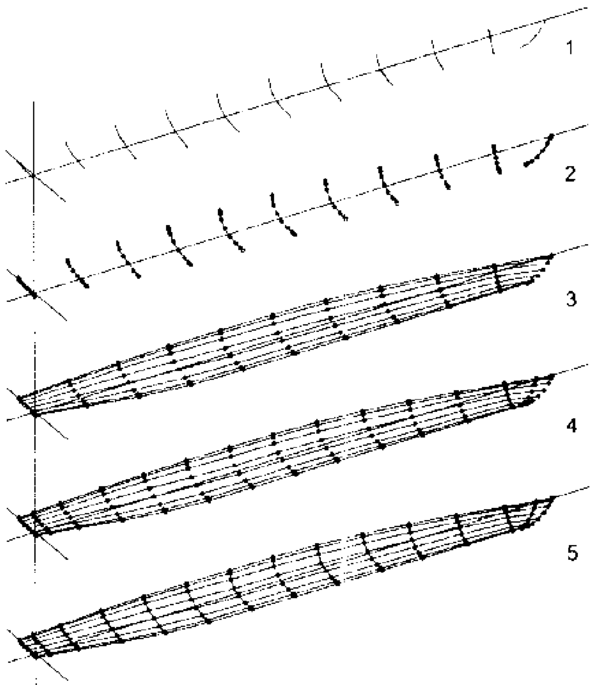

Figure 11. Steps of the fair skinning interpolation – Design sections and bow contour for underwater part of monohull $D1$

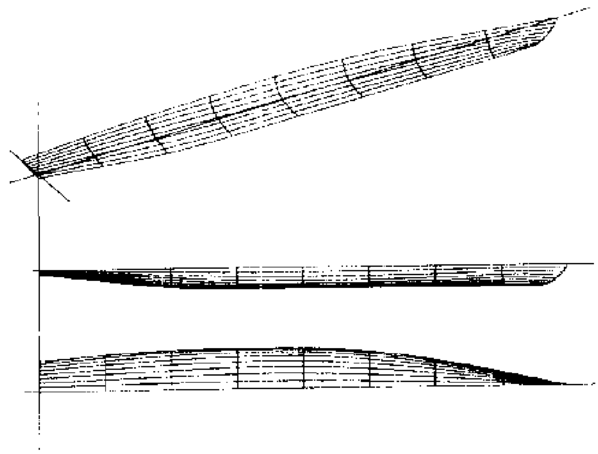

Figure 12. Perspective, side and top views of the skinning B-spline surface for underwater part of monohull $D1$

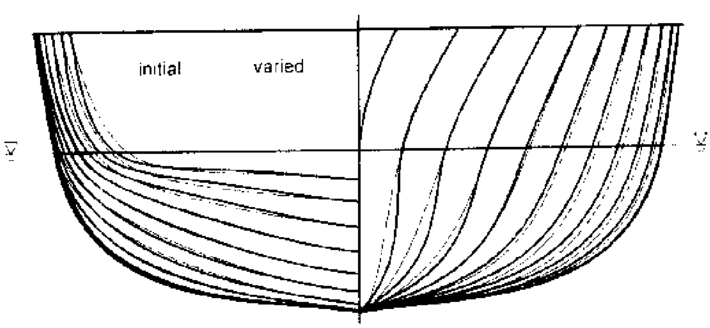

Figure 13. Comparison of fully form parameter designed monohulls – Monohull $D1$ (initial) and automatically derived vessel (varied) with decreased wave resistance

Figure 2 depicts the final form parameter generated surfaces for both the underwater part and the freeboard of $D1$. The following basic curves were used for this design task: SAC, DWL, CPC, DEC, TAB at the design waterline and TAE at the center plane curve, see again tables 1 and 2. Body plans of two alternative vessels are submitted in figure 13, the sections being derived from intersecting the surfaces with planes $x_{GS} = const.$.

It shall be pointed out that absolutely no manual vertex manipulations were performed: rather all shapes were purely derived from form parameter input. Given quantities like displacement, center of buoyancy, waterplane area and center of flotation were met with an accuracy of around 0.1%. The modeling examples required only a few CPU-seconds on a current PC with a 300 MHz Pentium processor for the an entire hull and considerably less for a single curve. Additional examples may be found in (Harries and Abt, 1997), (Harries, 1998) and (Harries and Abt, 1999), the former two being more elaborate with regard to ship design problems, the latter focusing on sailing yachts.

Design scenarios

Geometric modeling

Parametric curve and surface design requires that values for form parameters be known. In general a naval architect may not be able to immediately specify all form parameters needed to model an entire hull geometry from scratch. However, the introduced mathematical model permits that any form parameters beyond a small set of necessary (mainly positional) parameters may be left to be determined from the optimization if unknown at the beginning. They can then be modified and reintroduced into the optimization so as to gradually build up the final shape.

Frequently a design task starts from an available parent hull. In this case the existing vessel can be analyzed for its form parameter content and subsequently redesigned without any difficulties as has been done for the example monohull *D1*. Systematically varying the geometry then becomes a matter of simply and intuitively changing the values of selected parameters.

Approach to formal hydrodynamic optimization

This also opens the path to the second (and optional) design scenario of formal hydrodynamic optimization. In the proposed parametric design method a hull's geometry is created from its *direct* geometric properties, determining the vessel's hydro*static* conditions. The generated shapes accurately meet all specified form parameters and intrinsically acquire excellent fairness. Both features are key prerequisites for the systematic optimization of a hull's most important *indirect* properties – i.e., its various hydro*dynamic* qualities like resistance, propulsion and sea-keeping – and, consequently, the parametric method is well-suited for integration into a synthesis model of formal hydrodynamic optimization.

The synthesis model for hydrodynamic design as presented by (Harries, 1998) contains four stages:

1. Form generation via parametric design.
2. Fluid dynamic analysis by means of numerical flow simulation.
3. Design evaluation – for instance in terms of wave resistance.
4. Systematic variation driven by non-linear programming.

The optimization process commences with an initial set of free form parameters, i.e., the free variables of the hydrodynamic design problem. This set of form parameters is used as input to the first stage – shape design – in which the hull is parametrically generated within an inner optimization loop as discussed throughout this paper. The hull geometry is then passed on to the second stage – shape analysis – in which the flow field is computed using a state of the art Computational Fluid Dynamics (CFD) code. At the third stage – shape evaluation – the performance of the current hull is determined, yielding a hydrodynamic measure of merit by which to assess the geometry. At the fourth stage – shape variation – the measure of merit is examined to decide on a promising change of the free variables according to the chosen optimization strategy. In (Harries, 1998) a multidimensional conjugate gradient method is used in combination with a Golden Section line search. New values for the free form parameter are thus devised and then transferred to the geometric modeling process. The next round of the hydrodynamic optimization loop is started. In the end, a local optimum is found and the process is terminated.

Following this procedure an example wave resistance minimization was performed for the fast monohull *D1* at its design speed $F_n = 0.433$, see (Harries, 1998) for a comprehensive discussion. The wave resistance was computed with the non-linear potential flow code of the CFD system SHIPFLOW by (Larsson et al., 1990) after a careful reliability study had revealed good accuracy of ranking alternative hulls of the D-Series correctly (Harries and Schulze, 1997). In figure 13 the body plans of the initial design and a variation developed within the formal optimization are shown. The geometric changes deduced automatically display meaningful features like bulbous shapes close to the forward perpendicular, decreased angle of entrance of the design waterline and increased breadth of the transom. The displacement and the waterplane area were kept constant during the optimization by means of simply freezing these important form parameters. Promising reductions in resistance could be achieved. Compared to the initial hull the varied design given in figure 13 for instance encounters 7% less wave resistance and 4.5% less total resistance at $F_n = 0.433$.

Naturally, the accomplished improvements can only be as reliable as the computational model employed to analyze the flow field. One should therefore not expect the full advantage predicted and experimental validation studies are still required to prove the validity of CFD-based hydrodynamic optimization.

Conclusion

A new approach to the parametric design of ship hull forms has been presented. The shape of the envisioned hull is specified in terms of its desired form parameters from which basic curves are laid out. The basic curves then contain all information needed to derive a design section at any longitudinal position. An ordered set of design sections is created and then interpolated to produce an accurate and mathematically closed surface description.

Compared to previous methods major improvements are:

1. A B-splines curve representation is utilized which provides high flexibility and allows for the accommodation of any desired number and meaningful combination of form parameters.
2. Fairness criteria are applied at the early stage of shape definition rather than at the later stage of shape evaluation.
3. All important planar curves – the longitudinal basic curves and the representative design sections – are modeled in a unified way via optimization.
4. The common set of basic curves is extended by several more longitudinal curves which may be included depending on the modeling problem.
5. A new skinning interpolation for the generation of B-spline surfaces is introduced which also employs fairness from a functional point of view.
6. The entire process of hull shape generation is supported by form parameters without the need for a designer's interaction, e.g. manual point control.
7. The approach is thus well applicable to fully automatic hydrodynamic optimization.

Nevertheless, further research is required to develop the form parameter approach to its full potential. Regarding curve optimization for instance inequality constraints should be taken into account – e.g. to confine design sections to lie inside the hull's maximum permissible draft and beam and outside given hard points which may originate for example from predetermined container positions or structural considerations. Moreover, the parametric methods must be extended to complex hull forms which also feature bulbous bows, stern bulbs etc. These substantial design elements have yet to be suitably parameterized and adequately integrated.

It is the authors' firm believe that the form parameter approach to the design of fair hull shapes will play an important role in establishing a modern hull design methodology to the benefit of faster preliminary and better hydrodynamic design.

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PARAMETRIC GEOMETRY AND OPTIMISATION OF HULL FORMS

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Abstract

A method is presented for generating the surface of a ship hull from two-dimensional section curves. It is an extension of a method for the efficient parameterization of complex three-dimensional surfaces called the PDE Method. The method views surface generation as a boundary-value problem and produces surfaces as the solutions to elliptic partial differential equations.

Introduction

The geometry of ship hull surfaces is traditionally designed and represented by a set of curves, called the ship lines plan. Conventionally, ship lines are made up of plane curves, namely the waterlines, sections and buttock lines, which lie in orthogonal planes parallel to the coordinate axes. The curves in the lines plane together form a mesh of curves lying on the surface of the hull, from which a surface representation can be obtained by interpolation. This approach to hull design dates back many years, and although the advent of computers has transformed the drafting and fairing techniques used by ship designers and loftsmen, the favoured approach is still to design a surface in terms of a curve mesh, even when modern techniques for direct surface definition are available (for a discussion see Nowacki in [1]).

The introduction of techniques for Computer Aided Design into ship building has led to a new field of research called Computer Aided Ship Hull Design (CASHD) [2], a large proportion is concerned with the development of efficient techniques for curve definition and manipulation with which to produce a lines plan. In common with other areas of CAD, B-spline based techniques are popular in CASHD, e.g. [4,5,6,7,8]. For an up-to-date survey of these methods the reader is referred to reference [2].

Although large portions of a hull surface can be defined via ship lines, eventually a surface description of some sort must be constructed, and the problem of moving from a curve mesh to a mathematical surface description is another research area in which there is a great deal of activity, not only in the context of CASHD but in other application areas as well. For example Munchmeyer *et al* [3] describe developing a lines plan from B-spline curves and then producing a surface description by using biquintic Coons Cartesian patches.

The term often applied to the quality of a surface produced is fairness, and recently much effort has been devoted to techniques for automatically producing fair surfaces according to some quantitative measure, often related to surface curvature. For instance, Nowacki and Reese in reference [9] describe fairing a mesh of bicubic Coons patches by minimising the integral of the sums of the squares of the two principal curvatures over the surface; later Nowacki and coworkers [10] described generating a faired curve mesh, from which to generate a surface description, by minimising an elastic strain-energy functional.

Now although there is fairly general agreement that surface fairness is in someway related to the curvature properties of a surface, and also that fairing a surface by minimising the integral of some curvature-related property over the surface is a good way to proceed (see for example [11]), there is no real consensus as to what constitutes a unique measure of surface fairness. And as might be expected, there is an extensive literature comparing various approaches to the problem, i.e. the relative merits of different fairness measures, e.g. [12,13,15,16.17]. For recent review of the area the reader can consult reference [11], while [14] provides a comparison of results obtained using different measures of fairness.

In this paper we describe an approach to the generation of a hull surface from a lines plan definition based upon a method for surface generation known as the PDE Method, which adopts a boundary-value approach to surface generation and produces a surface as solution to an elliptic partial differential equation. The boundary conditions needed to produce a patch of PDE surface take the form of the curves making up the boundaries of the patch as well as associated derivative information. In the present context, the patch boundaries are obtained from a series of ship section curves defined at various stations along the length of the vessel. When designing using the PDE Method, a complex surface, such as that of a ship, is broken up into constituent patches which meet at space-curves ('characterlines') which form the boundaries between adjacent patches. Adjacent patches share common boundary conditions and thus continue to meet exactly throughout any changes to the overall geometry that may occur during the design process. This is in contrast to many conventional boundary representation systems, which typically use surface patches generated from polynomial spline functions, and often require 'trimming' at the boundaries where adjacent patches meet.

Although the PDE Method was originally envisaged as a technique for surface generation rather than representation, work has been carried out using the PDE Method to create a surface model of an existing object, for instance that of a marine propeller. Initially the method was used to create a qualitative representation of the surface, and then extended to a quantitative fit using data describing a real propeller [18,19]. According to current practice, propeller blades are usually defined by specifying the shape of sections at certain stations along the span of the blade. These sections are arranged so as to produce the desired load distribution for an efficient propeller. The PDE method can produce a marine propeller blade by a boundary-value approach where the two boundaries between which the surface is formed are a curve with a airfoil shape at the root of the blade, and a curve of vanishingly small size at the tip of the blade. By a suitable choice of derivative boundary conditions the shape of a marine propeller can be obtained. Furthermore, Dekanski [19] showed how an accurate fit with an actual propeller could be obtained by a suitable choice of boundary conditions. Subsequently work was carried out on the problem of producing a wing surface that interpolated a series of specified airfoil sections distributed at various points along the span [20].

The problem addressed in this paper is similar in aim to the above work in that we are seeking to produce a smooth surface that interpolates specified sections, in this case so that a hull surface is obtained. The present work differs from this earlier work in two important respects. Firstly, the curves through which the PDE surface is supposed to pass are no longer periodic, i.e. closed, so that the scope of the method is extended by the work described here. Secondly, once a PDE hull surface has been created, numerical optimization methods are used to automatically improve the quality of the surface.

In the next section we give an outline of the PDE method, while in the section following we describe the application of the method to the problem of generating a curvature continuous hull surface that passes through specified section curves. Finally we present some preliminary results obtained using the method.

Outline of the PDE Method

The PDE Method produces a smooth surface from boundary-data by generating the surface as the solution to a suitably chosen elliptic partial differential equation. The boundary-data typically takes the form of parameterised curves with associated derivative information which form the edges of the PDE surface patch. For example, work has been carried out upon solutions to the following fourth-order equation,

$$\left(\frac{\partial^2}{\partial u^2} + a^2 \frac{\partial^2}{\partial v^2}\right)^2 \underline{X} = 0 \tag{1}$$

which is solved over some finite region Ω of the (u,v) parameter plane, subject to boundary conditions which specify how $\underline{X}$ and its normal derivative $\frac{\partial \underline{X}}{\partial n}$ expressed as parametric functions of u and/or v, vary along the boundary of the region $\partial\Omega$. For example, if we were solving over the rectangular region $[0,1]\times[0,1]$ the function boundary conditions would take the form:

$$\begin{aligned}
\underline{X}(0,v) &= \underline{F_1}(v), \quad 0 < v < 1 \\
\underline{X}(u,1) &= \underline{F_2}(u), \quad 0 < u < 1 \\
\underline{X}(1,v) &= \underline{F_3}(v), \quad 0 < v < 1 \\
\underline{X}(u,0) &= \underline{F_4}(u), \quad 0 < u < 1
\end{aligned} \tag{2}$$

where the functions $\underline{F_1}(v)$, $\underline{F_2}(v)$, $\underline{F_3}(v)$, and $\underline{F_4}(v)$ give the shape of the curves bounding the surface patch, while the derivative boundary conditions

$$\begin{aligned}
\underline{X_u}(0,v) &= \underline{D_1}(v), \quad 0 < v < 1 \\
\underline{X_u}(u,1) &= \underline{D_2}(u), \quad 0 < u < 1 \\
\underline{X_u}(1,v) &= \underline{D_3}(v), \quad 0 < v < 1 \\
\underline{X_u}(u,0) &= \underline{D_4}(u), \quad 0 < u < 1
\end{aligned} \tag{3}$$

basically determine the direction in physical space in which the surface moves away from a boundary and how 'fast' is does so.

The partial differential operator in (1) represents a smoothing process in which the value of the function at any point on the surface is a weighted average of the surrounding values. In this way a surface is obtained as a smooth transition between the boundary conditions imposed on the function and its first derivative. Hence, PDE surfaces tend to be naturally smooth or fair since they do not possess any internal features that are not (in some sense) present in the boundary conditions. The parameter a controls the relative rates of smoothing between the u and v parameter directions. Indeed, when $a = 0$, the procedure reduces to a polynomial interpolation between corresponding v values on the boundaries, and as such this case is appropriate for generating plane sections of surface. The influence of a is important and can be used to 'spread' regions of high curvature very effectively. It can also be used selectively to prevent the propagation of unwanted boundary features into the bulk of the surface [21].

To make use of an efficient solution method [22] based upon a Fourier decomposition of the boundary curves, periodic solutions have often been considered in the past where, for example, equation (1) is solved over the (u,v) region $\Omega: [0,1]\times[0,2\pi]$, subject to periodic boundary conditions in the v direction. Topologically, the resulting surface is like a closed 'band' with the $u = 0$ and $u = 1$ iso-parameteric lines forming closed curves. In work on generating aircraft wings [20] for example, the $u = 0,1$ isolines corresponded to particular wing-sections through which the PDE surface was required to pass. However, in the present problem the curves through which the PDE surface is required to pass are section curves on a ship hull, and as such are not closed. Despite this, by using the method described in the next section, we can rapidly generate a curvature continuous PDE surface that passes through the given section curves and generates a complete hull surface.

Generating a Ship Hull from Section Curves.

The section data is given in the form of N plane section curves distributed at various stations along the length of the vessel, normal to the axis of the vessel. The sections are shown in Figure (1). To produce the complete hull surface, a patch of PDE surface was generated between each pair of section curves. Hence, except for the end sections, each section curve forms the boundary between successive PDE surface patches that meet along that curve. The boundary conditions imposed are chosen so that adjacent PDE surface patches meet with function, tangent plane and curvature continuity along their common boundary. To achieve this, solutions of the following 6th-order equation is used :

$$\left(\frac{\partial^2}{\partial u^2} + a^2\frac{\partial^2}{\partial v^2}\right)^3 \underline{X} = 0 \tag{4}$$

As mentioned above, a particularly efficient solution method exists for the case where periodic solutions to equation (4) are sought [20,22], but in the present application the boundary-conditions, i.e. the section-curves, are not naturally periodic. However, despite this, it is possible to extend the section curves so that they become periodic, and hence a hull surface can be generated very rapidly by the method described below. To achieve this what that is required is to connect an extra section of curve between the two end points of a section, as shown in Figure (2), and so make a complete loop. A convenient way of doing this, which is the method employed in this paper, is to add a circular arc between the two end points of the section-curve. The centre of the arc and its radius are chosen so that the circle meets the section curve with continuity of tangent direction, thus ensuring that the extended section curve is as smooth as possible.

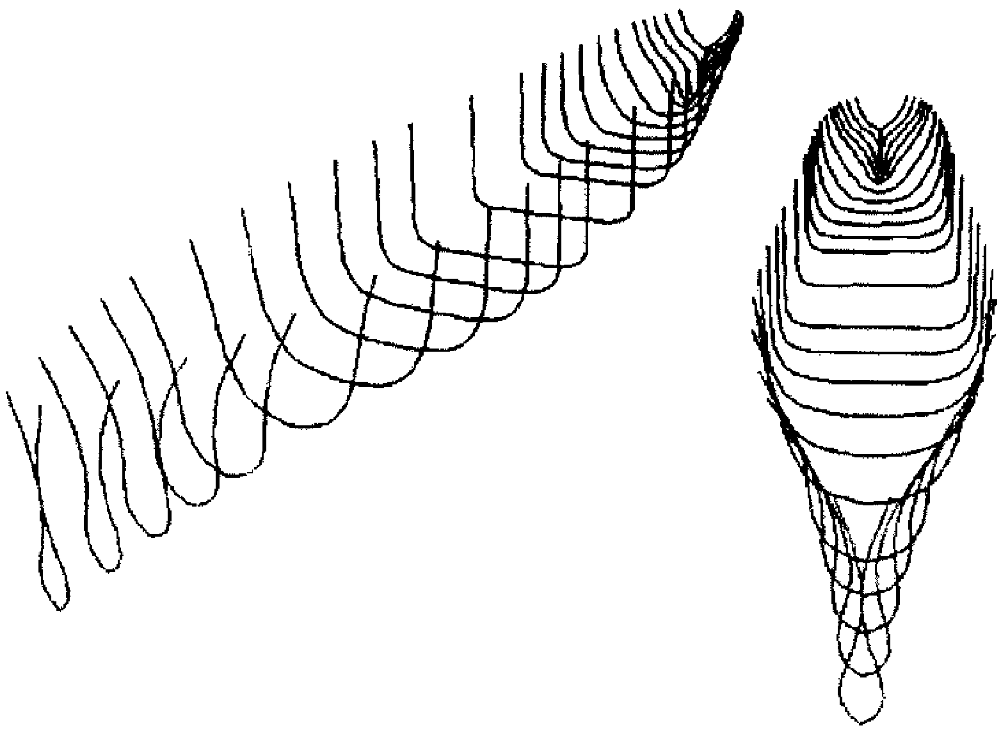

Figure 1: Two views of the section curves

To generate a complete hull, a periodic PDE surface is generated between each pair of extended boundary curves by solving equation (4) over the (u,v) region $[0,1]\times[0,2\pi]$. The function boundary conditions take the form

$$\begin{aligned} \underline{X}(0,v) &= \underline{S_0}(v), \\ \underline{X}(1,v) &= \underline{S_1}(v), \end{aligned} \qquad (5)$$

the boundary conditions on the first derivative of $\underline{X}$ are of the form

$$\underline{X}_u(0,v) = \underline{D}_0(v),$$
$$\underline{X}_u(1,v) = \underline{D}_1(v), \tag{6}$$

while the boundary conditions on the second derivative of $\underline{X}$ are of the form

$$\underline{X}_{uu}(0,v) = \underline{DD}_0(v),$$
$$\underline{X}_{uu}(1,v) = \underline{DD}_1(u), \tag{7}$$

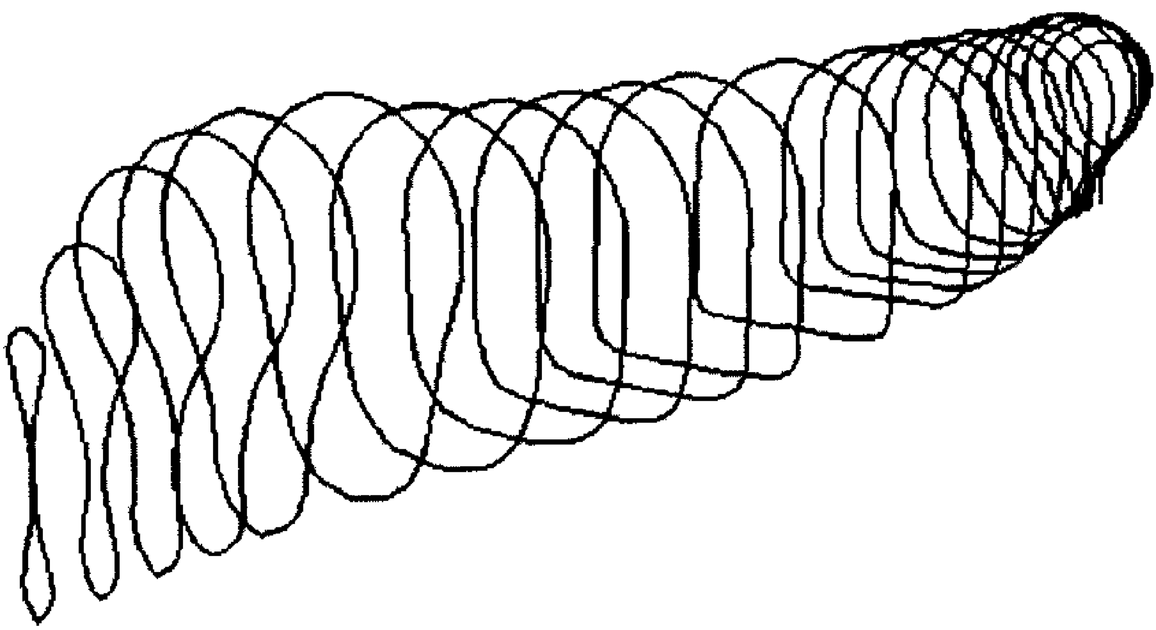

Figure 2: Extended section curves

The function boundary conditions $\underline{S}_0$ and $\underline{S}_1$ are obtained from the parameterization of the two extended section curves which must be chosen by the designer, subject to the constraint that corresponding ends of the original section curves are assigned the same value of the periodic parameter \$v\$, so that the portion of the solution surface corresponding to the physical hull can be easily extracted. The method used in this paper is to parameterize the section-curves in terms of arc-length.

The derivative boundary conditions $\underline{D}_0$, $\underline{D}_1$, $\underline{DD}_0$, and $\underline{DD}_1$, are obtained by finite-differencing the boundary curves, a process which will be described in more detail in the Results section.

In these circumstances we may write the solution of equation (4) in closed-form:

$$\underline{X}(u,v) = \underline{A}_0(u) + \sum_{n=1}^{M} \underline{A}_n(u)\cos(nv) + \underline{B}_n(u)\sin(nv) \tag{8}$$

where, depending on the boundary conditions, M may be infinite, and the 'coefficient' functions $\underline{A}_n(u)$ and $\underline{B}_n(u)$ are of the form

$$\begin{aligned} \underline{A}_0(u) &= \underline{a}_{00} + \underline{a}_{01}u + \underline{a}_{02}u^2 + \underline{a}_{03}u^3 + \underline{a}_{04}u^4 + \underline{a}_{05}u^5 \\ \underline{A}_n(u) &= \underline{a}_{n0}e^{anu} + \underline{a}_{n1}e^{-anu} + \underline{a}_{n2}ue^{anu} + \underline{a}_{n3}ue^{-anu} + \underline{a}_{n4}u^2e^{anu} + \underline{a}_{n5}u^2e^{-anu} \\ \underline{B}_n(u) &= \underline{b}_{n0}e^{anu} + \underline{b}_{n1}e^{-anu} + \underline{b}_{n2}ue^{anu} + \underline{b}_{n3}ue^{-anu} + \underline{b}_{n4}u^2e^{anu} + \underline{b}_{n5}u^2e^{-anu} \end{aligned} \tag{9}$$

where the $\underline{a}_{n0}$, $\underline{b}_{n0}$, etc. are constant vectors.

Now, since the extended section-curves and derivative boundary conditions are periodic in the variable v, we can express them as Fourier series. If these series are finite, then by matching the Fourier series expression (8) for the solution and its derivatives with the Fourier series expansion for the imposed boundary-conditions, it is straightforward to calculate the values of the constants $\underline{a}_{n0}$, $\underline{b}_{n0}$, etc. in the solution (8), and hence the solution itself. Now in general it is not possible to express the boundary conditions as finite Fourier series, but in spite of this it is still possible to find an approximate solution that exactly satisfies the boundary-conditions in the following way.

Note that the extended section-curves and derivative boundary conditions can be written as the sum of a finite Fourier Series with M terms plus 'remainder' functions $\underline{Rs}_i(v)$, $\underline{Rd}_i(v)$, $\underline{Rdd}_i(v)$ containing the higher order Fourier modes:

$$\underline{S}_i(v) = \sum_{n=0}^{M} \underline{Cs}_i^n(u)\cos(nv) + \underline{Ss}_i^n(u)\sin(nv) + \underline{Rs}_i(v) \quad i = 0,1 \tag{10}$$

$$\underline{D}_i(v) = \sum_{n=0}^{M} \underline{Cd}_i^n(u)\cos(nv) + \underline{Sd}_i^n(u)\sin(nv) + \underline{Rd}_i(v), \quad i = 0,1 \tag{11}$$

$$\underline{DD}_i(v) = \sum_{n=0}^{M} \underline{Cdd}_i^n(u)\cos(nv) + \underline{Sdd}_i^n(u)\sin(nv) + \underline{Rdd}_i(v) \quad i = 0,1 \tag{12}$$

The approach is to choose a value for M in equations (10), (11), (12), and approximate the extended section-curves and boundary conditions by a finite Fourier series, i.e. ignore the remainder functions, and use the procedure outlined above to generate a surface $\underline{\tilde{X}}(u,v)$ that interpolates these 'approximate' sections and satisfies the 'approximate' boundary conditions. Then the following 6 'difference' functions are defined

$$\underline{dS}_i(v) = \underline{S}_i(v) - \underline{\tilde{X}}(u,v) \tag{13}$$

$$\underline{dD}_i(v) = \underline{D}_i(v) - \underline{\tilde{X}_u}(u,v) \tag{14}$$

$$\underline{dDD}_i(v) = \underline{DD}_i(v) - \underline{\tilde{X}_{uu}}(u,v) \tag{15}$$

Then to obtain a surface $\underline{\bar{X}}(u,v)$ that exactly satisfies the boundary conditions, the following function is defined

$$\underline{R}(u,v) = \underline{r}_0(v)e^{au} + \underline{r}_1(v)e^{-au} + \underline{r}_2(v)ue^{au} + \underline{r}_3(v)ue^{-au} + \underline{r}_4(v)u^2e^{au} + \underline{r}_5(v)u^2e^{-au} \tag{16}$$

which is required to satisfy the conditions

$$\underline{dS}_i(v) = \underline{R}(u_i,v) \qquad \textit{for } u_i = 0,1 \tag{17}$$

$$\underline{dD}_i(v) = \underline{R_u}(u_i,v) \qquad \textit{for } u_i = 0,1 \tag{18}$$

$$\underline{dDD}_i(v) = \underline{R_{uu}}(u_i,v) \qquad \textit{for } u_i = 0,1 \tag{19}$$

of which there are sufficient to determine the 6 functions $\underline{r}_0(v),\ldots\ldots,\underline{r}_5(v)$ in equation (16), and then finally $\underline{\bar{X}}(u,v)$ is given by

$$\underline{\bar{X}}(u,v) = \underline{\tilde{X}}(u,v) + \underline{R}(u,v) \tag{20}$$

The physical hull surface itself is extracted from that portion of the periodic solution that lies between the v values corresponding to the end-points of the original section curves.

This procedure can be viewed as a means of generating an approximate solution (20) to equation (4) that exactly satisfies the boundary conditions and interpolates the specified extended section curves. The choice of M will obviously affect how good an approximation (20) is to the actual solution of equation (4), but since the higher-order Fourier modes decay exponentially, M does not often have to be very large for the difference between the approximate solution $\underline{\bar{X}}(u,v)$ and the exact solution $\underline{X}(u,v)$ to be negligible. Note that in choosing $\underline{R}(u,v)$ to be of the form (16) we are, in effect, Solving (4) with $a = a(n)$ (for more details see reference [22]).

In some circumstances, in particular in the results presented in this paper, the section-curves are specified as data points distributed around the sections, rather than as closed-form expressions. These cases can be treated using essentially the same method as outlined above, either by first interpolating (or approximating) each section curve using some sort of spline function to obtain a closed-form expression, or by using discrete Fourier transforms and a discrete version of equations (13), (14) and (15) where the functions $\underline{r}_0(v),\ldots\ldots,\underline{r}_5(v)$ are expressed discretely.

Results

In this section we show some results of using the method. The original section curves used to generate the hull surface were provided by courtesy Ian Applegarth of the UK office of Kochums Computer Systems. The complete set of sections are shown in Figure (2). To produce a patch of PDE surface between each pair of section curves, boundary conditions must be derived from these section curves which are provided in the form of discrete points. As mentioned above, the function boundary conditions were obtained by reparameterizing each curve in terms of arc-length and distributing an equal number of points around each section. Each curve was then extended so that it became periodic; and again each extended curve had an equal number of points it. The derivative boundary conditions imposed at each data point were then obtained by finite differencing the function values at corresponding points v_j on neighbouring curves using central differences in the obvious way, i.e.

$$\begin{aligned} \underline{D}^0(v_j) &= \frac{1}{2}\left(\underline{S}^+(v_j) - \underline{S}^-(v_j)\right) \\ \underline{\underline{D}}^0(v_j) &= \left(\underline{S}^+(v_j) - 2\underline{S}^0(v_j) + \underline{S}^-(v_j)\right) \end{aligned} \tag{21}$$

where the superscript 0 refers to a value at the section in question, whilst the superscripts + and - refer to values at the section curves on either side. To ensure the required degree of continuity between successive surface patches, i.e. up to curvature continuity, the same boundary conditions were imposed at each section curve in the solution for both of the surfaces that share the boundary. The derivatives at the end sections were estimated using one-sided differences with quadratic accuracy. It should be noted that although this is a convenient way of ensuring curvature continuity, there can be more independence between patches in the choice of the boundary. However, the conditions necessary to otherwise ensure curvature continuity are non-linear and costly to impose, especially in the optimisation of the hull surface which is described below.

The resulting hull surface is shown in Figure (3). Note that the value of 0.1 has been used for the smoothing parameter a; the number of Fourier modes M that have been used is 8; and the value of the factor ω that controls the decay of the remainder function is $8a$. As indicated above the original hull sections have been reparameterized in terms of arc-length. To generate the figures, 40 data points

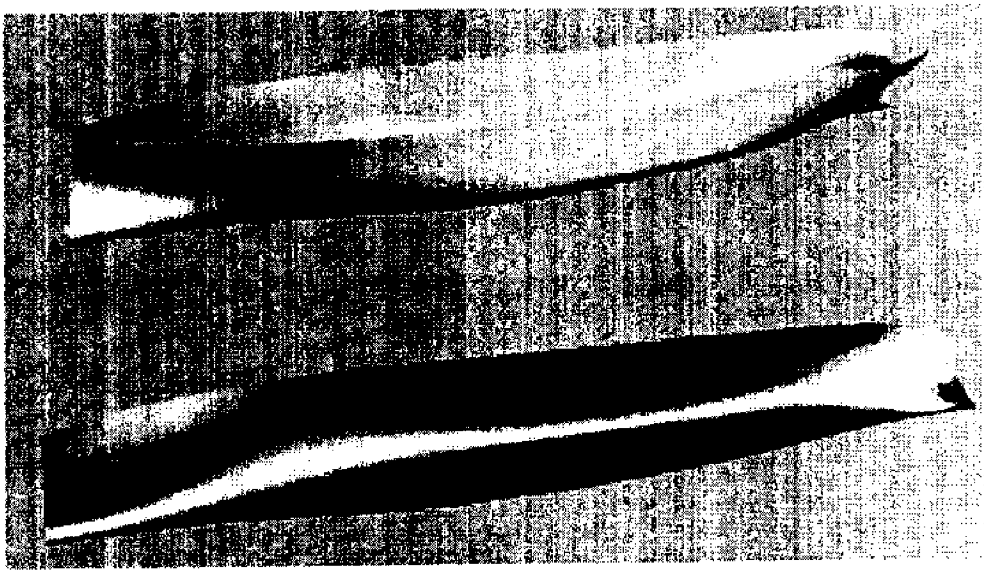

Figure 3: PDE hull surface passing through the entire set of section curves.

have been taken around each section with 11 data points between each section to produce each PDE surface patch. Note that the process of generating a complete hull from the original section data takes only a few seconds on a 400 MHz Pentium II PC. Figure (3) shows that a smooth, realistic hull surface has been produced. In order to assess the fairness of such surfaces, plots of the various types of surface curvature are often given across the surface, e.g. [11,13,14]. Unfortunately, the regions of high curvature at the bow and stern dominate such plots for this surface. Therefore, Figure (4) shows the shape and Figure (5a) a plot of mean curvature across it, for a surface that passes through some of the intermediate sections, for which the shape change is not too drastic.

Figure 4: PDE hull surface passing through intermediate sections

From Figure (5a) one can see that the distribution of mean curvature across the surface is fairly smooth. This is a combination of the fact that the PDE Method tends to produce naturally fair or smooth surfaces, and the fact that equations (21) are a sensible basis on which to choose the derivative boundary conditions. However, it is possible to improve upon this choice of boundary conditions by introducing weighting parameters wd_i and wdd_i that multiply the derivatives at each section, thus

$$\begin{aligned} \underline{D}^0(v_j) &= \frac{wd_i}{2}\left(\underline{S}^+(v_j) - \underline{S}^-(v_j)\right) \\ \underline{D}^0(v_j) &= wdd_i\left(\underline{S}^+(v_j) - 2\underline{S}^0(v_j) + \underline{S}^-(v_j)\right) \end{aligned} \tag{22}$$

and then vary the values of the weighting parameters by numerical optimisation so as to improve the value of some measure-of-merit for the curvature distribution over the surface.

The results of just such an optimization are shown in Figure (5). The initial starting design was that shown in the Figure (4). The algorithm used for the optimisation was the standard *Broyden-Fletcher-Goldfarb-Shanno* (BFGS) algorithm as described in Press *et al* [23]. The number of sections used to generate the hull surface was 12, hence the number of parameters in the optimisation was 24, which takes a few minutes to run on a 400 MHz Pentium II PC. The objective function that was minimised was a discrete measure of the curvature variation across the surface, namely:

$$\iint \nabla^2 H \, dA \tag{23}$$

where H is the mean curvature and dA is an element of surface area. This integrand is a measure of the deviation of the mean curvature at point from the average value of surrounding points, and gives an estimate of curvature variation.

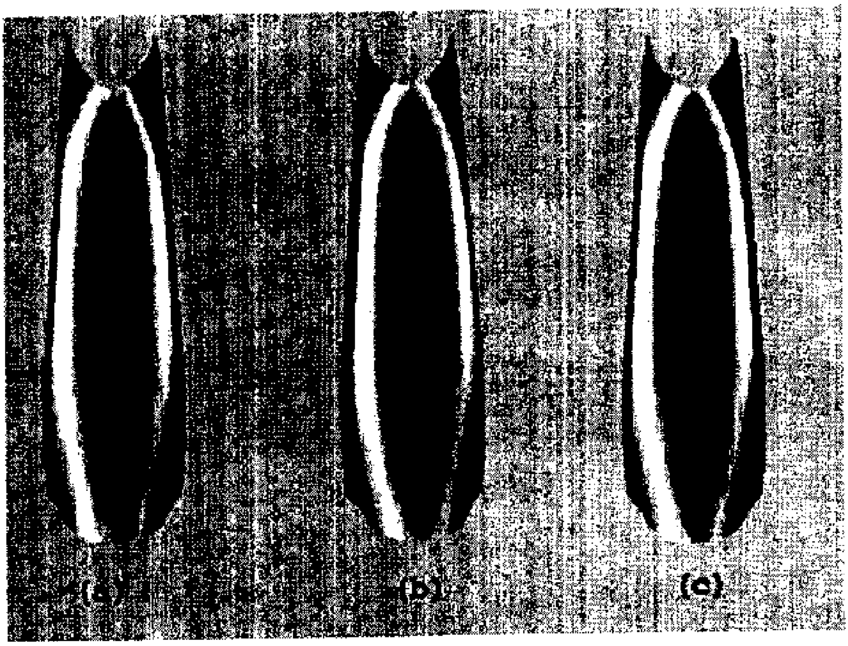

Figure 5: Distribution of mean curvature over (a) original hull, (b) optimised hull (a=0.5) (c) Optimised hull (a=0.1).

The results are given in the form of grey-scale plots showing the distribution of mean curvature over the optimised and the original, unoptimised, surface. The number of Fourier modes used to generate the surface was 8, a was 0.5, and ω was $8a$. Although it is not clear from the grey-scaling, the curvature distribution is more even for the optimised surfaces, and in fact the value of the measure of merit on equation (26) has been reduced by about a fifth. Note that the size of the maximum and minimum values of the curvature have not been significantly affected by the optimisation. Also included for the sake of comparison is an optimised hull for the case where $a = 0.1$.

Conclusions

The results presented in this paper are of a preliminary nature intended to show the potential of the method and indicate that that it has some merit. The surfaces produced by using it show a smooth curvature variation, and from the initial section data, a complete description of the hull can be produced in a matter of seconds. Further work needs to be carried out on the automatic optimisation of the surface, for instance in the choice of design parameters that are varied in the optimisation. For example, at present the factors that weight the derivative boundary conditions imposed at the sections, and which were varied during the optimisation, were taken as constants around each section. To increase the range of shapes accessible to the system, these weighting factors could be allowed to vary around each section, although this would introduce more design parameters and consequently increase the cost of the numerical optimisation. Furthermore, the use of alternative objective functions in the optimisation could be explored. For instance one based on Gaussian curvature might be used to produce a surface that was as close to developable as possible, and so enhance the manufacturability of the surface. Or else an objective function directly related to some functional measure of merit such as viscous or wave resistance could be used, e.g. [24].

Finally it should be noted that once a suitable final design has been obtained, the PDE surface description can be converted into a standard spline-based representation suitable for transfer to other CAD systems [25].

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DEVELOPMENT OF PRACTICAL 3-D LINES FARING SYSTEM FOR SHIP HULL FORM(MELFAS) AND ITS APPLICATION TO CIMS

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Abstract

The research and development on Computer Integrated Manufacturing (CIM) systems has been carried out intensively by shipyards for years in order to increase the efficiency of the whole process of design and production of ships. Also, utilization of Computational Fluid Dynamics (CFD) is being pursued for the development of hull forms with better performance in the seaway. One of the most important technologies of these developments is the precise digital expression of hull forms ready for use by the computer software and its efficient generation in short design period.

Practical hull forms are composed of 3-D surface components, some of which are complicated ones, others are gradually changing delicate ones. Although many kinds of enhanced surface patches are available, it is still difficult task, from the practical view point, to generate the faired and precise 3-D digital hull surface model.

Mitsubishi Heavy Industries, Ltd. (MHI) has been carrying out R&D on the practical lines faring and hull surface expression method for years and has developed the integrated lines faring and 3-D surface generation system called "MELFAS (Mitsubishi Expert Lines Fairing system for Ships)". MELFAS has been put into practical use in the ship model basin of the Nagasaki Research & Development Center. At the same time, MHI has developed the first simultaneous 5-axis numerically controlled model ship milling system for towing tank tests by useing of the 3-D surface data generated by MELFAS, and through these systems integration, the hull form development and its verification work in the ship model basin has been much improved.

Furthermore, the hull form digital data generated by MELFAS has been transferred to the shipyard CIM system MATES and continuously applied to the ship design and production. This has eliminated detailed hull surface fairing for production which had been successively carried out in the design department and led to a shorter design period.

In other words, design process re-engineering has been achieved through the integration of MELFAS and the shipyard CIM. Thus, MELFAS greatly contributes to the shipyard CIM system.

In this paper, the authors present the advanced characteristics of "MELFAS" and its applications in various fields, such as precise and efficient fairing work, transmission of hull form data to numerically controlled model ship milling machine, and delivery of hull form data to the design and construction departments of the shipyards.

Introduction

In hull form design, performance estimation by Computational Fluid Dynamics (CFD) is being used in addition to performance evaluation by the towing tank test. At present, the development of the shipbuilding CIM, which is aimed at an increase in efficiency of the design and production, has been carried out in forward thinking shipyards. One of the most important technologies of these development is the precise digital expression of hull forms ready for use by the computer software. This technology is also required for the development of numerically controlled milling system for model ship for the towing tank test, and propeller, etc.

Usually, 3D CAD system is prevailing and these system provides advanced surface generation/manipulation functions. However, it is still difficult to express the hull form precisely because the hull form has several unique characteristics on surface shape comparing with other products.

MHI has developed the new hull fairing system with high accuracy for the wire frame model and also developed advanced surface manipulation system by customizing the ready made surface CAD system. These two system has been integrate as a surface design system. Using this system, whole hull form including bow and stern has been expressed precisely. At the same time, MHI has developed the numerically controlled model ship milling system for towing tank test by use of the 3-D surface data generated by this system. Furthermore, the hull form digital data generated by this system has been transferred to the shipyard CIM system MATES and continuously applied for the ship design and production. The fairing work, which had been carried out several times in research department, initial design, and production design stage, has eliminated to only once in research department. And, reduction of design period and cost has been realized.

This paper describes the advanced characteristics of this system and its applications in various fields, such as precise and efficient fairing work, transmission of hull form data to numerically controlled model ship milling machine, and delivery of hull form data to the design and construction departments of the shipyards.

Traditional Hull Form Design and Faring Workflow

Traditional Faring Workflow

Hull form design is composed of two tasks. One is hull form planning so that the required performance in seaways and the demand for the arrangement of hold and tanks are satisfied. The other is hull form faring so that the hull surface has adequate fairness and accuracy as the 3-dimensional free form surface. Traditionally, the faring had been carried out several times by design department, towing tank and production engineering section to satisfy their own required accuracy and fairness because the required level differs for design task, model test and parts lofting. Figure 1 illustrates a traditional workflow of hull form design.

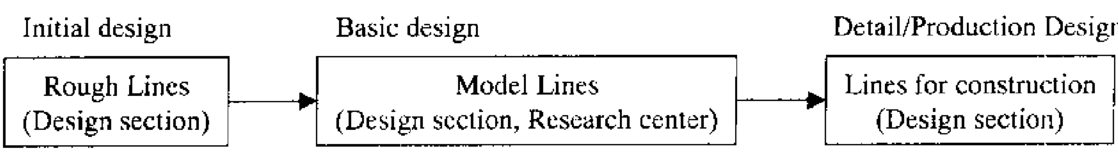

Figure 1. Traditional Workflow of Hull Form Design.

- Initial Design Stage: "Rough lines" is generated as initial hull form based on the type ship stored in the hull form database. Principal dimensions and tank arrangement are main interests at this stage.

- Basic Design Stage: Initial hull form is examined and refined from the view point of performance in seaways and "Planned lines" are generated. Then, "Planned lines" is refined and faired into "Model lines". The frequent communication about tank arrangement is performed between design department and towing tank. The "model lines" is verified through the towing tank test and the hull form below the load water line is fixed.
- Detail/Production Design Stage: Finally, "Lines for designing work" is faired to be more accurate "Lines for Construction". This is used for parts lofting and construction in production department.

Thus, in the traditional workflow, hull lines are refined and become more accurate step by step through the fairing work performed in several sections.

Demands for Fairing Process Re-engineering

In this way, the faring work is a collaborative task between design department and the R&D department. Furthermore, faring task is performed several times in different sections because the required accuracy level for hull surface is different in each section. However, the advancement of information technology, related to the surface geometry expression/handling and surface data transfer, gives the possibility to define highly accurate hull surfaces, applicable to the actual ship construction, in rather early hull form planning stage. If this could become possible, the hull form design and faring workflow would be simplified, the design period would be shortened, and the design efficiency will be improved.

Furthermore, the efficient hull form generation and faring in towing tank makes it possible to shorten the model test period. This enables us to fix the hull form earlier and leads to the early start of design work and also enable to shorten the total design period. So it is highly desired to use the software tools which enables us to do the faring task efficiently, to shorten the verification period in towing tank and to provide the accurate hull form data to shipyard CIM system.

Survey of Commercial Software Products for Hull Form Design

In order to realize our goal, we firstly surveyed the commercial software products. These days, many commercial software products are available for hull surface generation and lines fairing through interactive operations. These software have functions to define hull form. These software are roughly classified into following two types.

2D-Lines Fairing System following traditional fairing process

The software in this category follows the traditional 2D-lines fairing approach, i.e. 2D curve fairing using batten and weights. It expresses the hull form through a wire frame model. Three sectional planes and its intersected curves (frame lines/ waterlines / buttock lines) are used to define the hull form. Several kinds of curves such as spline curves and arcs are used to express 2D sectional shapes. The consistency between sectional curves on three kinds of plane have to be guaranteed by the operator. This way of fairing is easy to handle the curves and fit the image of experienced workers. However, this method can not provide a smooth surface and it is difficult in general to keep the consistency among sectional curves on three kinds of plane. The result of fairing work rather depends on the operator's skill.

3D-Surface Fairing Using Control Lines

This method defines hull form using 3D surface patches which are generated from 3-dimensional control curves. Firstly, 3-dimensional control points both on the body plan and stem/stern profiles are defined, as base reference points for the hull surface. Secondly, these control points are connected and fitted by 3D spline curves, and a wire-frame model is generated. Thirdly, the surface patches are defined by use of these wire-frame model. This method can generate rather smooth 3D surface efficiently and fit the image of the hull form planing engineer. However, many control points and, consequently, fine meshed wire frame control curves have to be added, If that hull form is complicated (such as having large surface curvature change). In this case, the strong points of this method are weakened.

Some Comments for Commercial software products

These commercial software are specially developed for the hull form fairing. Therefore all these software provide necessary functions for hull form fairing and makes it possible to do an efficient fairing task. However, these software seem to assume traditional hull forms. For example, some systems cannot express special hull forms such as un-symmetrical stern end, catamaran ships and submersible vehicles. They can't express propeller and the appendages such as bossing, etc. Therefore, there are problems for the fairing and surface generation that is required in ship hull form design in a wider sense. In other words, their functions for surface generation and manipulation capability are not so strong compared with generally applicable and advanced surface modeling ability that mechanical CAD systems usually provide.

In conclusion, the commercial software which provides both enhanced surface manipulation functions and special features necessary for hull surface fairing don't exist. Furthermore, the CAM functions to generate cutter passes for model and propeller milling machines, which are very important for hull form development and most of the mechanical CAD systems provides, are not available in these commercial software at the moment.

Development of 3D Hull Form Design and Faring System : MELFAS

Based on the understanding of the state-of the-art of the hull-form CAD system, we have decided to develop our own system, which was later named Melfas (Mitsubishi Expert Lines FAiring system for Ships).

Functional Requirements for MELFAS

Primarily, requirements for our system are as follows;

- To realize the fairing system which does not depend on the operator's skills, especially the consistency of frame lines, waterlines and buttock lines are kept automatically at all times. Surface smoothing can be done.
- To perform efficient rounding for the end part of bow and stern where a large amount of work time is always required comparing the fairing with the main hull.
- To be applicable not only for traditional hull forms, but for all kinds of hull forms, such as catamaran ships and submersible vehicles.
- To be able to do the fairing of appendages such as bossing, propellers which can not be expressed in mathematical forms, and offshore structures.
- To enable to generate surface patches efficiently and easily using fairing results. These

patches should be accurate enough to be directly used in detailed/production design.

- To provide the surface information to the shipyard CIM system MATES.
- To be able to generate NC data for NC model ship milling system with simultaneous 5-axis control.
- To provide enhanced surface manipulation functions with good user interface equivalent to a general purpose mechanical CAD system has.

Development Concept of MELFAS

To fulfil the requirements shown above, functions of 3D surface CAD system are absolutely necessary. However, it is considered very difficult to accomplish the fairing work by using the functions of the existing 3D surface CAD system only, into the fairness which is presently accomplished by skilled workers. Therefore, we decided to adopt the basic concept of a combined system, which has both functions of general-purpose 3D CAD system based on a surface model and lines fairing system in 2D based on a wire frame model.

We selected an advanced 3D CAD system as the core system and customized it by adding specific functions which are prepared by MHI on the basis of long-term experience in hull form design to express unique and complicated features of hull surface. The core system provides us with good GUI. The specific functions enable us to handle hull parts by gently changing and freely curved surface which characterize a ship's hull, and parts of the surface at fore/stern ends with a big change in curvature.

As for the CAM functions to be used for the model ship milling, we have decided to customize the original CAD system functions.

System configuration of MELFAS

MELFAS is a practical hull form fairing and surface generation/manipulation CAD/CAM system based on MHI's experience and know-how in shipbuilding. MELFAS is an integrated system with fairing capabilities specific to hull fairing, and advanced CAD capabilities of a general purpose 3D CAD system. Figure 2 shows the system configuration of MELFAS. The main software components of MELFAS are as follows.

- "Hull fairing function" to define highly accurate hull forms with wire-frame models.
- "Automatic rounding/fairing function" for end parts at the bow and stern where large change of surface curvature exist.
- "Surface CAD" to apply surface patches and provide hull form data to NC system and the shipyard CIM system MATES.

These three(3) functions are linked firmly and the information generated by one program can be transferred freely. Therefore, the wire-frame data and surface data is transferred to the surface CAD components very easily. The functions of these programs are described in the following sections.

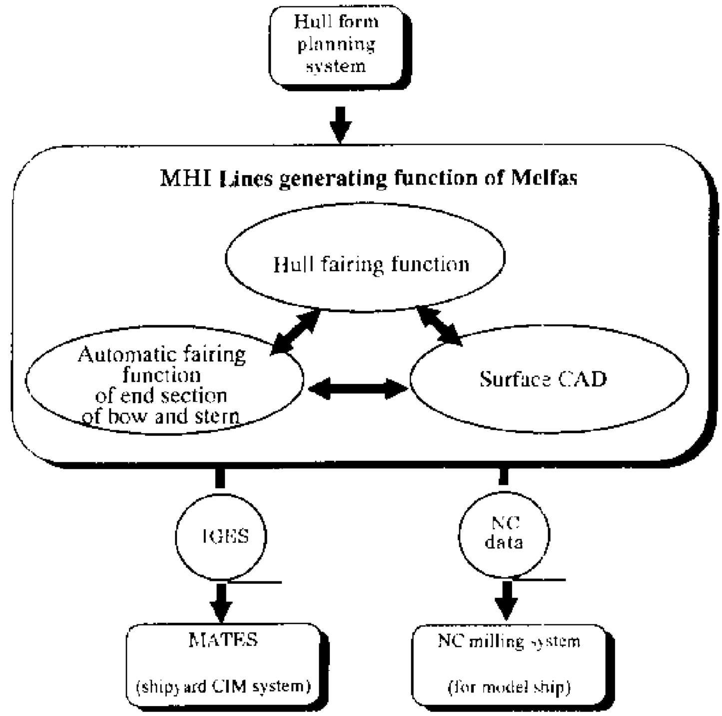

Figure 2. System configuration of MELFAS

Hull fairing function

Hull fairing function is composed of more than 10 sub-programs which provide specific functions necessary for the fairing of a hull surface. The operator can perform fairing work smoothly through the comprehensive windows specially designed for considering efficient fairing process.

Figure 3 shows screen images of 3-dimensional fairing sub-systems. The hull form is expressed by 3-dimensional wire-frame model. The operator can perform 3-dimensional fairing work automatically keeping the consistency of frame lines, water lines and buttock lines. The control curve expressed as a 3-dimensional space curve is also used to help the fairing work. The type of continuity of the curve and the target region of fairing can be defined as attribute data, and the offset point is defined as a fixed point or a movable point. These fairing conditions can be easily set through the buttons arranged on the graphical windows.

A large variety of fairing support functions are provided, for example, verifying the surface fairness, slicing the hull surface with an arbitrary plane, curve fitting by spline/mathematical formulae/arcs, and display functions such as zooming and rotating are also available. One of the features of this sub-system is that fairing on a 3-dimensional rotating coordinate system can be performed efficiently. This function is effective for the fairing of propellers.

In this way, the user can perform hull fairing work very efficiently and can do the fairing with high accuracy.

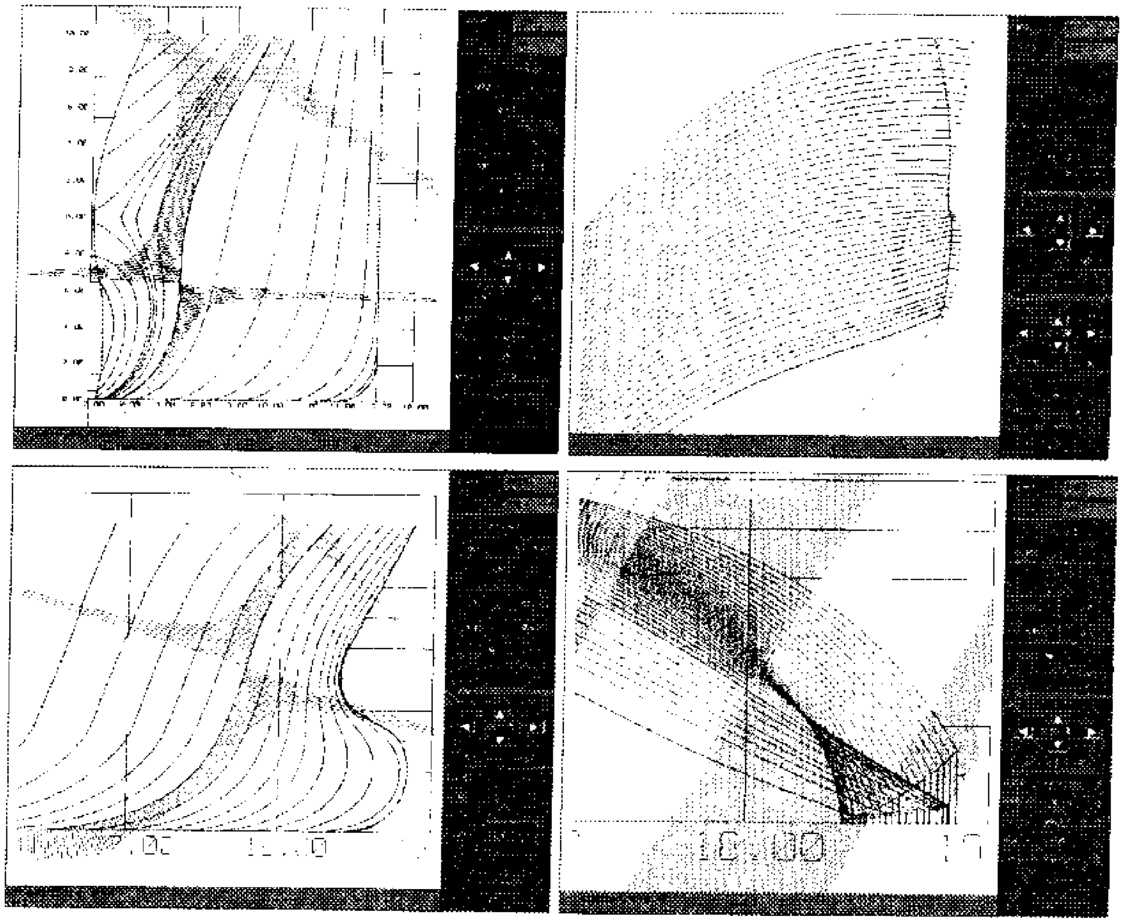

Figure 3. 3-dimensional fairing program.

Automatic fairing function of bow and stern ends

Figure 4 shows a screen image of the automatic fairing function of a bow end. In general, it is difficult to connect the gently curved surface of the main hull with the hull surface of the bow/stern ends with a big curvature. Also, fairing the hull parts near the bow and stern is very time consuming. This sub-system can perform the fairing of bow and stern parts almost automatically by use of mathematical formulae implemented in this sub-system. The generated surface can be connected smoothly to the main hull surface while keeping a connected condition. In this function, mathematical representation of hull surfaces are defined based on MHI's practice in consideration of propulsion performance and productivity in the production department. The result can be confirmed at once by way of a 3-dimensional screen image. By use of this sub-system, fairing work hours at bow and stern end has been much shortened, and highly accurate hull form surfaces have been obtained with ease.

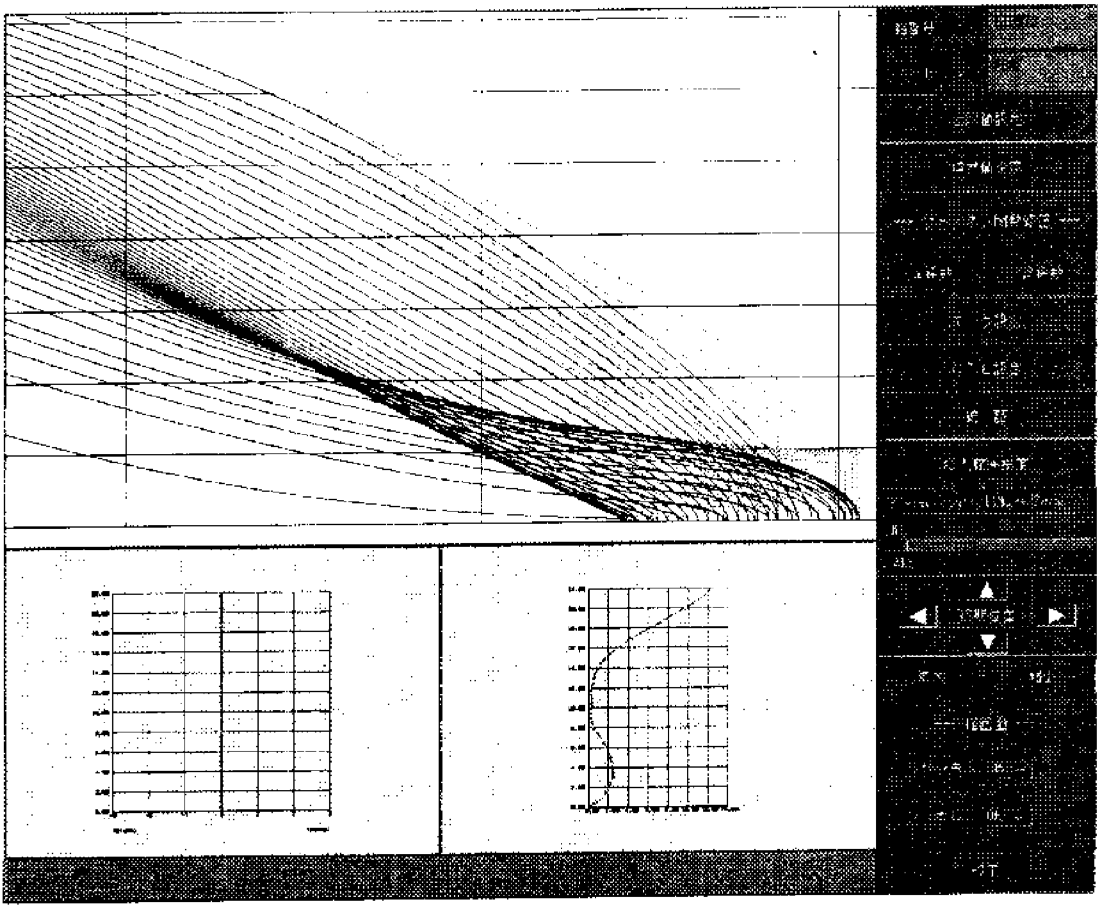

Figure 4. a screen image of automatic fairing function of bow end section

Surface CAD

Several functions which are necessary to model the ship hull form have been added to customize a ready made 3D CAD system for general use. A surface model of hull form can be defined efficiently by the sub-system when a wire-frame model is prepared by the above mentioned fairing sub-systems. This sub-system provides a very enhanced viewing operation by use of functional devices such as a dial switch and a joy stick. The real-time rotation and zooming of the model can be done very smoothly. This function contributes to the verification of surface fairness, and the efficiency of fairing work has been much improved. It has also the function to verify a surface. Figure 5 shows the examples of screen image for the verification of a surface. The left one shows normal vectors at numerous points on a surface and the right one shows "highlight lines" which are reflection of line light sources. By use of these screen image, the operator can check the fairness of a surface quite easily.

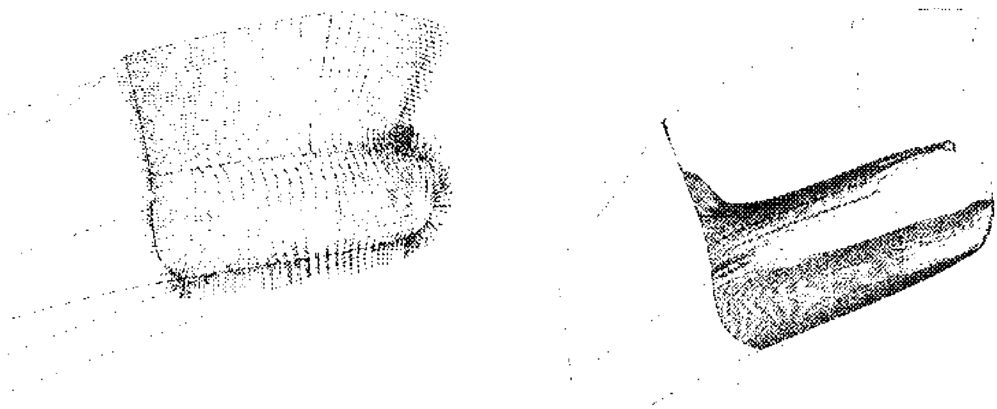

Figure 5. Verifying the surface model

As this sub-system has been developed on the basis of an advanced CAD system, this sub-system has very strong surface modeling function. Figure 6 shows the stern part of a hull form, and figure 7 is an example image of a high speed craft. Not only the hull form but also the parts with geometrical shape, such as propeller, rudder, shaft bracket and bossing and super structures can be expressed easily as shown in these figures.

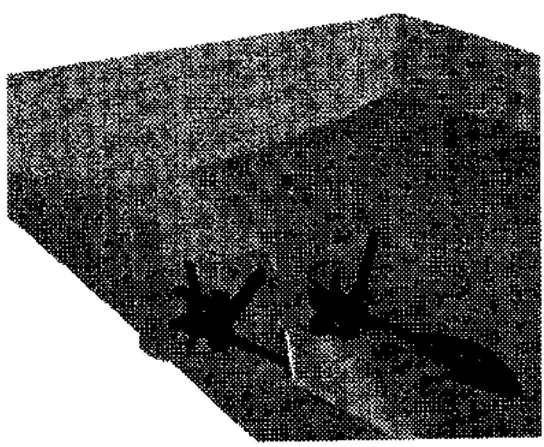

Figure 6. Stern view of hull form including propeller, rudder, and shaft bracket

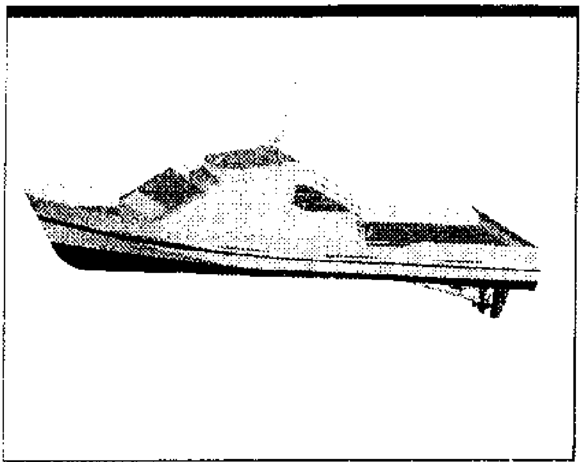

Figure 7. An example of high speed craft

In addition to the surface manipulation function mentioned above, this sub-system provides several functions to support hull form design work. For example, calculation of displacement, area of wetted surface, curve of center of buoyancy, generation of offset data and coordinate of frame line can be performed by this sub-system.

Numerically Controlled Model Ship Milling System

Current NC system for model ship

The size of the model ship used for the towing tank test is about length of 6 - 10m. The NC milling system for the model ship is usually the gantry type, and the work piece is fixed to the table of the pit. Usually, it has two cutter units symmetrically arranged. A milling cutter, ball-end-mill and a straight-end-mill is used for cutting the model ship.

Most of these milling systems adopt the simultaneous 2.5 axis control along the waterline of the constant Z value. There does not seem to be an NC milling system that can produce a complete model of the whole ship including the complicated surface of the bow and stern.

Development of the 5-axis numerically controlled model ship milling system

By developing the surface generation system, MELFAS, an accurate hull form can be expressed for the whole ship hull form including a bulbous-bow and stern-tube. MHI has developed the world's first simultaneous 5-axis numerically controlled model ship milling system using 3-D surface data generated by MELFAS. The specification of this system is shown in table 1.

Table 1. The specification of 5-axis numerically controlled model ship milling system

Universal head (with automatic tool exchange fasility)	2set
Max. stroke(X axis)	10.4m
Max. stroke(Y axis)	2.5m
Max. stroke(Z axis)	1.3m
Rotation angle of arm (The direction of rotation of the z axis)	$\pm 270^{\circ}$
Rotation angle of arm (The direction of a parallel plane of Z axis)	$\pm 95^{\circ}$
Max. milling speed	10m/min

For the NC data preparation, a CAD/CAM system installed on the high speed graphic work station is used. This software can be applied not only to the hull form but also to general structure. The NC data (cutter pass) of the simultaneous 5 axis control processing and the simulation of the cutter head are shown in the figure 8.

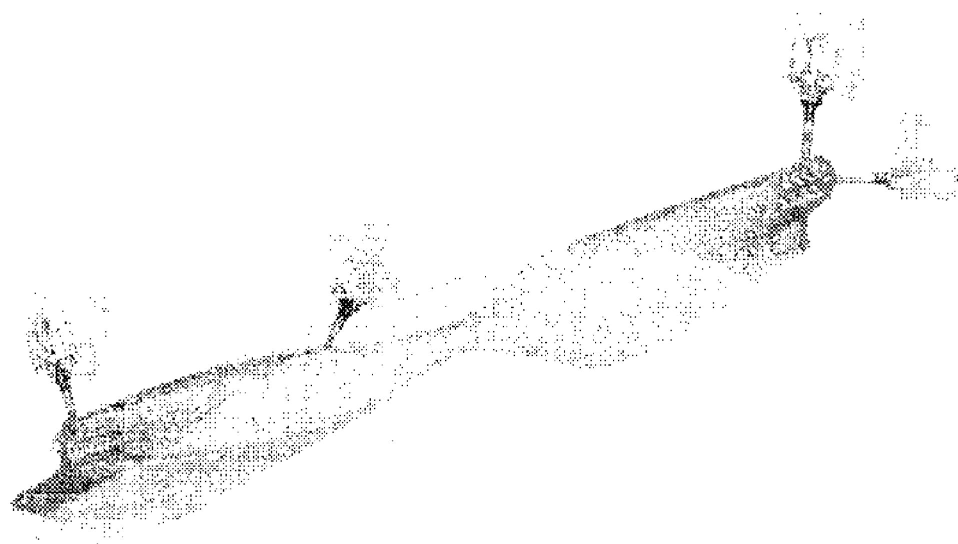

Figure 8. The simulation of the cutter head

Figure 9 shows a model ship under process. In this figure, the milling process of the aft hull, and the rough cutting process for the fore hull have been finished. The final cutting to refine the surface still remains to be done.

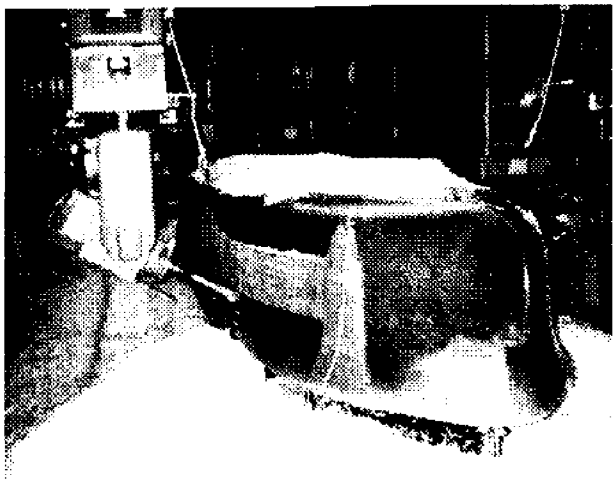

Figure 9. A model ship during the processing

As the usual model ship NC milling machine had a simultaneous 2.5 axis control, it couldn't make the complete hull form, especially in the bow and stern areas, and much manual work for surface refinement remains. However, this system can produce a complete hull surface as shown in figure 9. Accompanying work, such as drilling of the thruster tunnel and the layout of the waterline for photographing the wave height measurement, is also carried out by this system. This NC milling system can be used for not only the model-ship but also for the model-propeller, model-inlet of water jet, and for a topographical model in a wind tunnel test. Figure 10 shows a model-propeller during the milling process.

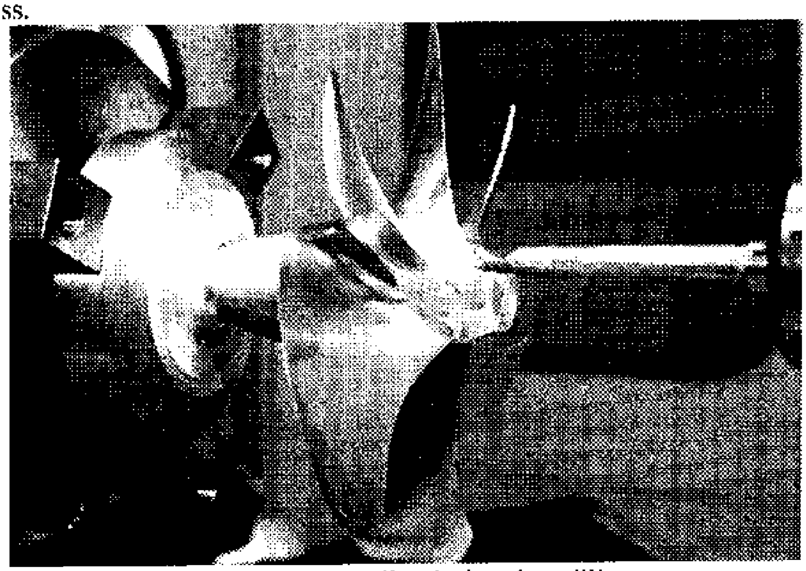

Figure 10. A model-propeller during the milling process

Integration with Shipyard CIM System

As was explained in the previous section, the required accuracy for hull surface differs in each stage; initial design, model for the towing tank test, preliminary design and the parts lofting stage. Additional work for the hull surface refinement had been carried out in these design stages so that it has adequate accuracy for its stage's design work. Also the information transfer of hull forms had been performed by means of offset data and/or primitive points coordinates data of hull lines. This implies that the poor transferring function had caused information omission and the less accuracy.

On the other hand, the shipyard CIM system has already been constructed and put into practical use. The explanation of CIM system at MHI was reported in the previous ICCAS paper. The shipyard CIM system is composed of MARINE, MATES, factory automation system and production management systems. Therefore, if the very accurate hull form data is enough to adopt for the parts generation in the digital form, it is prepared at the beginning of design. Considerable improvement of design efficiency is expected. Due to the efficient generation of the highly accurate hull form and information based on the surface modeling function of MELFAS, it becomes possible to improve the hull surface information produced for the model test into more accurate surfaces applicable to actual ship construction, and to provide it to the shipyard CIM system, MATES.

The surface data transfer from MELFAS to MATES is performed by IGES format. MATES uses commercial software product as the geometry modeling kernel, so the surface information is smoothly exchanged without any deterioration of accuracy between both systems. The faring work, which had been carried out several times in different design stages, has been unified into a one time execution in the towing tank by use of MELFAS. When doing the faring for the test model, the succeeding refinement such as consideration of thickness effect etc. for the actual ship usage is considered beforehand. Immediately after the performance of the model ships has been verified through the model test, the model surface data is refined into the actual ship's surface data by use of the MELFAS' very advanced surface manipulation function. In this way, it becomes possible to transfer the accurate surface information to the design department. The faring work in the design department has been completely diminished. Also the design process has been much improved as the confirmed data is provided at the beginning of design stage. The design lead-time has been much shortened and design alteration related to the hull form has been scared. Improvement of design accuracy contributes to the elimination of re-work in the production stage and improvement in the design workflow. In other words, the optimization of design and production has been much promoted.

It is a well known fact that the data exchange between two different CAD systems arises accuracy discrepancy problem. To counteract this problem, some enhanced functions such as automatic re-projection of the trimming boundary of the trimmed surface patches and automatic verification function for the opening of the adjacent patch boundaries has been implemented. Furthermore, the standardization of how to make patches for the hull form has been achieved in the operation level.

The integration of MELFAS and MATES has realized not only the elimination of doubly input work but also the improvement of efficiency of shipyard CIM system. It can be said that the shipyard CIM system has been extended to the upstream direction.

Conclusions

1. MHI has developed practical lines faring and hull surface design system MELFAS on the basis of MHI'S long term experience and know-how of shipbuilding. MELFAS provides not only ship specific faring features which enables to do the faring work very efficiently, but also advanced surface generation/manipulation function based on the commercial surface CAD system for general use. The combination of these two functions makes MELFAS a very unique and advanced system.
2. Accurate digital data of hull surface can be generated by MELFAS at very early design stage. This digital data can be transferred to shipyard CIM system MATES and directly used in ship design. This eliminates re-works in the design department. Also this has realized a shorter design lead time and improvement of design accuracy. In other words, design process re-engineering has been achieved through the integration of MELFAS and MATES.
3. MHI has been first to develop a simultaneous 5-axis numerically controlled model ship milling system for towing tank test by use of a 3-D surface data generated by MELFAS, and through these systems integration, hull form development and its verification work in the ship model basin has been much improved.

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Assembly and Construction

THREE-DIMENSIONAL NUMERICAL SIMULATION OF PLATE FORMING BY LINE HEATING

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Abstract

Line Heating is the process of forming (steel) plates into shape by means of localised heating often along a line. Though any focussed heat source will do, the inexpensive and widely available oxyacetylene gas torch is commonly applied in ship production.

Over the years, many researchers have addressed the problem of simulating the process, and although very few have been successful in gaining accurate results valuable information about the mechanics has been derived. However, the increasing power of computers now allows for numerical simulations of the forming process using a three-dimensional thermo-mechanical model.

A general numerical analysis tool for the process has been developed for use with the commercially available finite element code ANSYS. It models the three-dimensional thermo-elastic-plastic behaviour of a plate being heated along a straight line between any two points. There is taken account for temperature dependant radiation, convection, conduction, Young's modulus and tangent modulus (in a bilinear plasticity formulation) in the modelling.

The model provides information not otherwise available, i.e. plastic response due to the heat treatment, time history of the temperature field, residual stresses, sensitivity to input parameters, etc. Further, empirical relations can be derived from the analysis. Once available, the empirical data (relating temperature field and local deflections) may be used in an optimisation procedure utilising pure elastic analysis—telling where and how much to heat to obtain a desired shape.

This paper will present the three-dimensional FE model and analysis results, along with derived empirical relations, and sensitivity analysis of the model.

Introduction

The motivation for the present study is the need to obtain simplified relations between input parameters such as plate thickness, torch speed and heat input, and final local deflections. This need arises if an iterative optimisation procedure is going to be used to predict the heating patterns. Direct iteration is not feasible, because the problem is already large. Instead of using hours per iteration in a fully thermo-mechanical analysis, only seconds are required with the empirical data at hand. A series of simulations with varying parameters has been carried out, and by using multivariate analysis, relations between the parameters and local plastic strains have been derived.

The Numerical Modelling

A model that simulates the line heating process should posses the following properties:

- It must consist of as few elements as possible to save valuable computing time.
- There should be a sufficiently fine mesh in the heated area to ensure a converged solution and precise description of the final deflection state.

- The model should be physically large enough to provide boundary conditions for the heated region, as would a real plate.
- Material properties and constitutive relations should correspond to the actual behaviour of the material.

Choice of Mesh

Convergence analyses have indicated that at least six linear solid elements should be used through the thickness, and that approximately 15-20 linear elements should cover the plastic zone perpendicular to the heating path. This applies when using a torch width (discussed later) of 4 cm. Convergence tests also reveal that linear elements are much more efficient—measured in computation time—than quadratic elements even for the same accuracy.

These requirements have led to a model, where a refined mesh with six elements through the thickness and 18 elements perpendicular to the path in the heat-affected zone makes a transition into a coarse mesh that is only one element thick, as shown in figure 1. The model allows the heating to start and end in any two points inside or outside the plate's edges—the latter option to allow edge effects to be investigated. The mesh will then be cut at the edge of the plate, see figure 2. If the distance between the two points is large, more blocks of fine elements will be inserted. Further, all properties such as thickness, torch speed, and input flux are input as parameters, making the model very versatile.

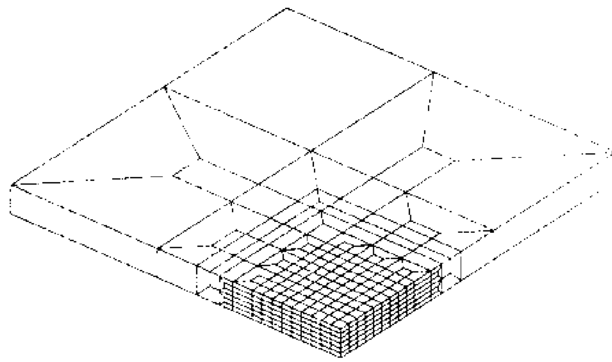

Figure 1: Part of the mesh that makes transition.

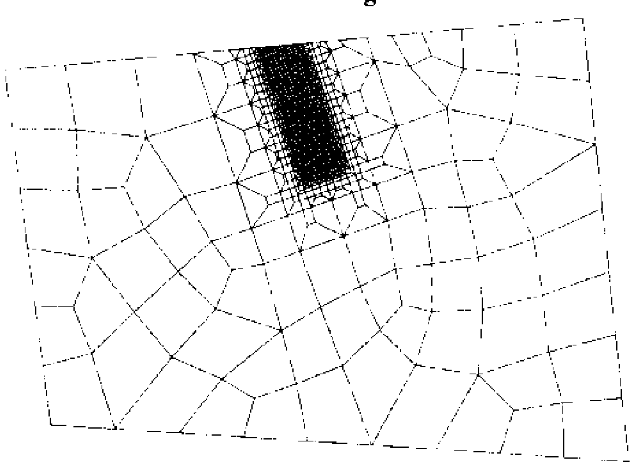

Figure 2: Fine mesh cut at the edge of the plate.

Heat distribution

The heat is applied as an axisymmetric Gaussian distributed flux, which is not necessarily a precise representation of the actual heat flux absorbed by the plate from a gas torch. Nevertheless, it is simple and generally accepted by researcher in the field of line heating, [3], [6] and [11]. The heat flux is

$$Q'' = Q''_{\max} e^{-\gamma r^2} \tag{1}$$

where Q'' is power per unit area, $Q''_{\max}$ is the maximum flux at the centre of the plate, γ is a distribution factor and r is the distance from the centre. To be able to assess the size of the heated area, a measure is defined as the radius where the flux is 1% of $Q''_{\max}$. This quantity is called the 'torch width' throughout this paper.

Cooling of the plate is modelled by free convection and radiation. The theory of free convection is adopted from [2], pp. 460ff, which describes convection on a uniformly heated plate. Convection as a function of temperature is shown in figure 3. As the plate subjected to line heating is heated locally, the physical conditions are not similar. However, conduction in the steel is prevailing compared to both radiation and convection, and therefore it merely serves as a way to allow the average plate temperature to descend to room temperature after a while. For that reason, the convection term is modelled as the average convection flux at 7.5 $^{W}/_{Km^2}$. Radiation is modelled by the Boltzmann equation, with emissivity at 0.5. As with convection, radiation is negligible compared to conduction.

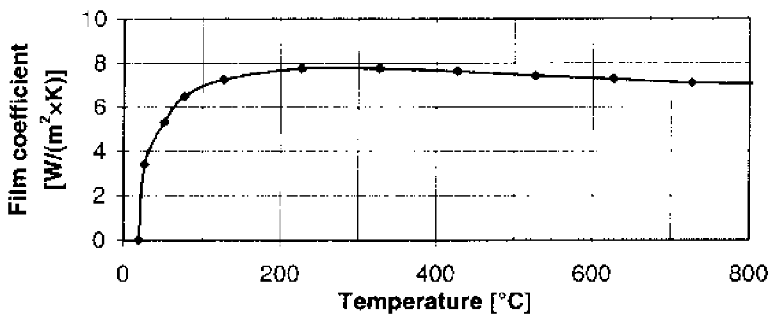

Figure 3: Heat convection film coefficient, based on average temperature of plate surface and quiescent air.

Material Properties

Material properties are adopted from [4] and are verified with data from [7]. It represents mild steel in a bilinear isotropic hardening plasticity formulation, defining Young's modulus and a constant tangent modulus for various temperatures. Though it is questionable, whether the data are sufficiently precise, and whether the constitutive relations (elastoplastic formulation rather than viscoplastic) are adequate to describe the real nature of the thermomechanical process of line heating, it will have to do. Material property data is very difficult to come by, even for the very simple case of elastoplasticity—it becomes even more difficult to find data for viscoplasticity. Material properties are shown in figures 4 through 6. The influence of changes in the yield limit is investigated in the section Sensitivity Analysis later in this paper.

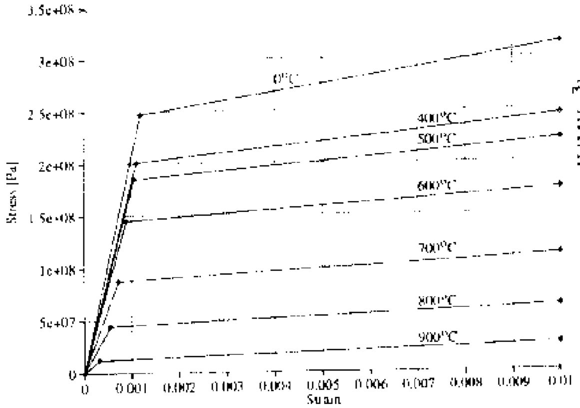

Figure 4: Stress-strain curves

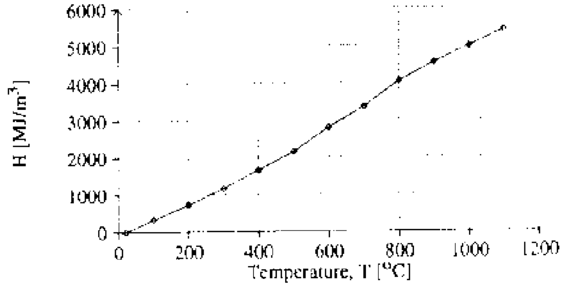

Figure 5: Enthalpy

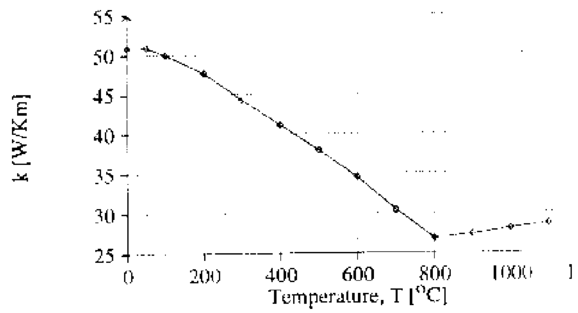

Figure 6: Thermal conduction properties.

Simulation Programme

Among the factors that control the final shape of the plate are plate size, heating line position, torch speed, power of the heat source, plate thickness, material properties etc. To gather relations from a sensible number of simulations, the number of unknowns must be reduced. Therefore, focus is put on the *local* deflections, as they supposedly are more general than the description of the total deflection of the plate—this more or less removes the result's dependency on plate size. Considering only plates of identical material and neglecting edge effects (position of heating line), the problem is reduced to depend on physical measures as thickness, torch speed and amount of heat.

In [11], parameters based on input power, Q, plate thickness, h, and torch velocity, v are found from dimensionless analysis. The quantities h and v are easily measured, but how much heat, Q, that is actually absorbed by the plate is difficult to say. Also inspired by the dimensionless analysis in [11] one gets the idea that the maximum temperature is very important, as any similarity in results prescribes similarity of the temperature fields. The maximum temperature is easily measured, and it is a function of the other parameters, Q, v, and h.

For these reasons only maximum temperature, T_{max}, plate thickness, h, and torch velocity, v, are considered in the simulation programme. As seen in the section Empirical Relations, good agreement between residual plastic strain and quantities based on these three parameters is found.

The simulation programme must cover a representative range of the possible parameter values. Three thicknesses (10, 15 and 20mm), three velocities (5, 10 and 15 $^{mm}/_{s}$) and three maximum temperatures (500, 600 and 700°C, reference temperature at 20°C) are chosen. These are believed to be adequate. Though the line heating process is used and approved by classification societies up to 900°C, [5], lower temperatures may be sufficient, "... because efficient bending was already being performed with lower temperatures" (quoted from [5] p. 6). Embrittlement is also more likely to occur at higher temperatures. Further, the constitutive model is unable to model temperatures above the phase transformation temperature of low carbon steel (723°C). Among others, the thermal expansion coefficient, the yield limit and Young's Modulus are different in heating and cooling during the phase transformation, [8]. This is the reason for not using higher temperatures than 700°C.

All in all the choice of parameter ranges causes 27 (3^3) simulations to be carried out. For details, refer to Appendix A.

The calculations are made for a 1x½ m plate with symmetry conditions. Heat is applied along a 20cm path on the long side (x-direction) at the centre of the plate (from point A to B in figure 7). A torch width of 4cm is used. This model consists of 5100 elements and 6380 nodes, spending about 10 computer hours on a Hewlett-Packard workstation[1] running ANSYS 5.3.

It is found that even for this short heated distance the plastic strain reaches a constant value independent of the position of the points A and B. Consequently all results are evaluated along a line perpendicular the heating path at the centre.

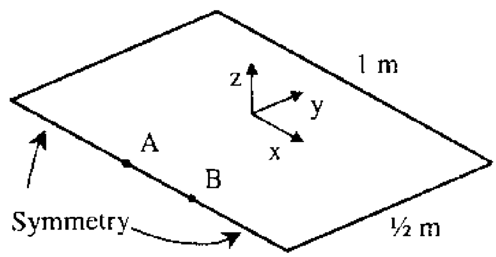

Figure 7: Sketch of model

Empirical Relations

To establish relations between the input parameters and the complex results from the three-dimensional simulations some simplifications must be made. The aim is to be able to extract the local deformations from the analysis and apply them locally to an elastic analysis later. Data is extracted from the heated zone only, which is assumed to be of same length as the heated path and having the average breadth of the plastic zone in general—shown as the shaded area on figure 8. A zone of equal size must then be applied to the elastic analysis.

Simplification

The following is done:

1. Evaluate only data from the section, *S*, perpendicular to the middle of the heating path, see figure 8. This is the same as assuming constant plastic strain along the x-direction, which is not completely true.
2. The plastic strain in the section, *S*, is averaged in the y-direction. The average plastic strain in either x- or y-components, $\hat{\varepsilon}^{P}_{x,y}$, can be expressed as

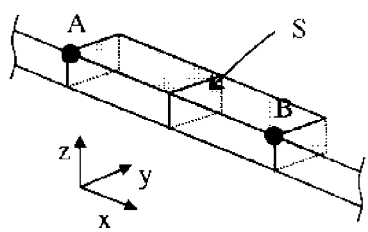

Figure 8: Heated zone

[1] HP Visualize C200 with 1GB RAM, benchmarked by HP to 21.4 SPECfp95.

$$\hat{\varepsilon}^{p}_{x,y} = \frac{1}{w^{p}} \int \varepsilon^{p}_{x,y} \, dy \tag{2}$$

where w^p is an average width of the plastic zone, $\varepsilon^{p}_{x,y}$ is the plastic strain x- and y-components respectively, and the integration is done over the full width of the plastic zone. This is done in every layer of elements through the thickness, giving average values for every layer. The width, w^p, is in average 3cm in all the 27 simulations, which means that the average strain in an elastic analysis must be applied to a 3cm wide zone.

3. The results are linearised in order to divide the strain into shrinkage and bending contributions to the strain field. The integration above yields a distributed average plastic strain that is everything but linear, so with the method of least squares a line is fit to the average strain data This is a very efficient way to simplify the data, and it can be done as illustrated in figure 9. Shrinkage strain, $D_{x,y}$, is calculated as the linearised value at the centre of the plate, while bending strain, $B_{x,y}$, is calculated as the difference between the linearised data at the surface of the plate and at the centre of the plate, see figure 9. Data for D_x, D_y, B_x, and B_y is given in Appendix A.

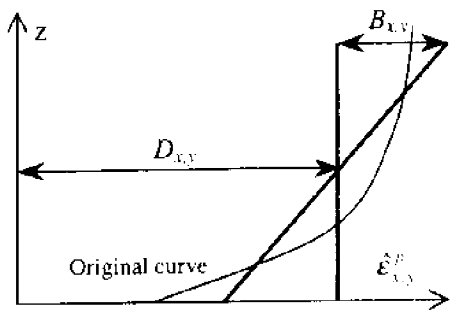

Figure 9: Linearisation of plastic strain

Empirical Relations

The empirical relations are derived using a multivariate analysis as described in [1] and [3]. With this method, one can find relations among a number of variables again using a least squares method to fit data. To find the parameters that D_x, D_y, B_x, and B_y depend on, a heuristic approach is taken: Almost any plausible important factor is tried for correlation with the four deflection parameters. Thus 87 different combinations of T, h, and v has been correlated with D_x, D_y, B_x, and B_y, yielding the correlation factors in the range [-1:1]. From the analysis, the combinations with the numerically largest correlation are chosen.

The regression is described with the following equation

$$Y_i = b_1 + b_2 X_{2i} + b_3 X_{3i} + \cdots + b_p X_{pi} + e_i \quad \text{or} \quad \mathbf{Y} = \mathbf{X}\mathbf{b} + \mathbf{e} \tag{3}$$

where $\mathbf{Y}$ is a column vector holding the dependant variables ($D_{x,y}$, and $B_{x,y}$), $\mathbf{X}$ is a $4 \times p$ matrix, that in every row, $i \in [1;4]$, holds the evaluated combinations of T, h, and v corresponding to Y_i. $\mathbf{b}$ are the coefficients for the best fit, and $\mathbf{e}$ are the residuals. Minimising the residuals yields:

$$\mathbf{b} = \left(\mathbf{X}^{T}\mathbf{X}\right)^{-1}\mathbf{X}^{T}\mathbf{Y} \tag{4}$$

Tables 1 through 4 show the best fit coefficients and the parameters of equation (2) along with the correlation constants.

Table 1: Expression for D_x

i	x_i	b_p	correl.
1	$2.4003 \cdot 10^{-4}$	1	-
2	$-1.6013 \cdot 10^{-8}$	T/h	-0.88
3	$-2.3410 \cdot 10^{-14}$	T^2/h^2	-0.86
4	$8.0298 \cdot 10^{-14}$	T^2/hv	-0.88
5	$6.1893 \cdot 10^{-15}$	T^2/h^3	-0.84
6	$-5.6027 \cdot 10^{-15}$	T^2/h^2v	-0.92
7	$-4.4606 \cdot 10^{-17}$	T^2/h^4	-0.81
8	$3.0442 \cdot 10^{-17}$	T^2/h^3v	-0.90
9	$4.5916 \cdot 10^{-18}$	T^2/h^2v^2	-0.80
Stdev: 4.7%, Max: 9.9%			

Table 2: Expression for B_x

i	x_i	b_p	correl.
1	$2.2733 \cdot 10^{-3}$	1	-
2	$-7.4826 \cdot 10^{-2}$	h	0.91
3	$-1.4490 \cdot 10^{-5}$	1/h	-0.94
4	$1.2501 \cdot 10^{-9}$	T/h^2	-0.88
5	$-2.9701 \cdot 10^{-11}$	T/h^3	-0.90
6	$1.7372 \cdot 10^{-13}$	T/h^4	-0.91
7	$-8.7183 \cdot 10^{-16}$	T/h^3v	-0.83
Stdev: 6.8%, Max: 17.2%			

Table 3: Expression for D_y

i	x_i	b_p	correl.
1	$-1.5744 \cdot 10^{-4}$	1	-
2	$-1.0900 \cdot 10^{-11}$	T^2/h	-0.85
3	$-2.4513 \cdot 10^{-14}$	T^2/hv	-0.93
4	$-4.3507 \cdot 10^{-15}$	T^2/h^2v	-0.94
5	$1.6332 \cdot 10^{-17}$	T^2/h^3v	-0.91
6	$4.8583 \cdot 10^{-18}$	T^2/h^2v^2	-0.85
7	$9.9642 \cdot 10^{-9}$	T/h	-0.79
8	$1.2582 \cdot 10^{-12}$	T/h^2v	-0.87
9	$-8.5846 \cdot 10^{-15}$	T/h^3v	-0.84
Stdev: 4.9%, Max: 10.7%			

Table 4: Expression for B_y

i	x_i	b_p	correl.
1	$-5.1117 \cdot 10^{-4}$	1	-
2	$-1.4358 \cdot 10^{-11}$	T^2	0.84
3	$-2.5431 \cdot 10^{-7}$	T	0.84
4	$1.0173 \cdot 10^{-11}$	T^2/h	0.74
5	$4.4639 \cdot 10^{-11}$	T^2/v	0.58
6	$2.7628 \cdot 10^{-13}$	T^2/h^2	0.55
7	$-2.6665 \cdot 10^{-13}$	T^2/hv	0.53
8	$-8.9016 \cdot 10^{-9}$	T/h	0.58
9	$1.5869 \cdot 10^{-12}$	Th^2v	-0.25
10	$-2.1899 \cdot 10^{-12}$	T	0.83
Stdev: 7.0%, Max: 16.1%			

Each fitting procedure's residual is represented by "stdev." and "max.", which refer to the standard variation and maximum value of the errors in each data set.

Validation

With these coefficients, it is possible to interpolate to yet unknown parameter values. As a test, an extra calculation is carried out with $T_{max} = 650°C$, $h = 12.5mm$ and $v = 8\ ^{mm}/_{s}$. The result from real simulation and from prediction is compared in table 5.

Table 5: Comparison of predicted and simulated data

Predicted	$-2.37 \cdot 10^{-4}$	$8.98 \cdot 10^{-3}$	$-5.84 \cdot 10^{-4}$	$5.08 \cdot 10^{-4}$
Simulation	$-3.74 \cdot 10^{-4}$	$2.05 \cdot 10^{-4}$	$-3.33 \cdot 10^{-4}$	$5.50 \cdot 10^{-4}$
Error	-37%	-56%	+75%	-8%

Unfortunately, the interpolation does not work very well! This may be caused by any of the following factors:

- Polynomials of too high order add noise when fit to only a few points. Either better polynomials or more data must be made.
- During the test programme, the new version 5.5 of ANSYS was installed. This made the analyses much more stable, but unfortunately it also changed the results from simulation. This means that it is difficult to predict new results from the results of the old version.

Obviously, the implementation of the multivariate analysis method still needs some refinement.

Applying Strain to an Elastic Analysis

Normally one cannot apply initial conditions as plastic strain to models in commercially available FE programs. In fact, ANSYS can only have displacements and temperatures as input. One way to apply the averaged strain is to use an artificial temperature field along with orthotropic thermal expansion coefficients. By using a mean temperature, T, a temperature difference from the upper side and the middle of the plate, ΔT, and different expansion coefficients in the x- and y-directions, α_x and α_y, it is possible to transfer the information. Based on the above definitions, the following holds true:

$$\alpha_x T = D_x \quad , \quad \alpha_y T = D_y \quad . \quad \alpha_x \Delta T = B_x \quad \text{and} \quad \alpha_y \Delta T = B_y \tag{5}$$

This is unfortunately an underdetermined equation system, leaving one parameter free, and forcing us to throw one equation away. The problem is, that the ratio of B_x/D_x must be equal to B_y/D_y. This is not always the case, as the ratio between the two ranges from 1 to 6.7. It is chosen to discard the equation with B_x, because bending in the y-direction is more important. Choosing T as fixed to a temperature T_1, this yields:

$$\alpha_x = \frac{D_x}{T_1} \quad , \quad \alpha_y = \frac{D_y}{T_1} \quad \text{and} \quad \Delta T = \frac{B_y}{D_y} T_1 \tag{6}$$

To test that this method may actually be used a simple model equal to the test No. 14 (T=600°C, h=15mm, v=10 $^{mm}\!/\!_s$) is made. Here the above mentioned ratio is 2.4. Figure 10 below shows a comparison of the test case and the elastic case evaluated for deflection in the z-direction at y=0m and y=0.5m. "Elast" denotes elastic equivalent analysis and "Orig" denotes original full

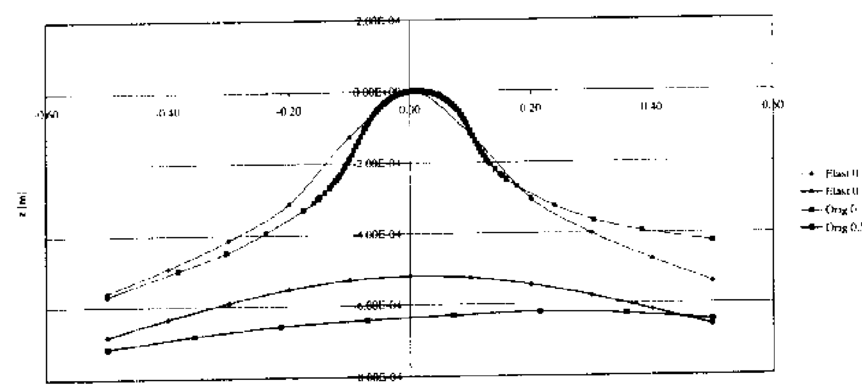

Figure 10: Comparison of full analysis and elastic equivalent case.

modelling. "0" and "0.5" are the y-coordinates.

As can be seen, a surprising good agreement is found between the elastic and the thermomechanical modelling—considering the assumptions and simplification. This can certainly be used for an approximate optimisation procedure and later be confirmed by an elastoplastic analysis.

Sensitivity Analysis

A smaller number of simulations have been made to examine the sensibility of the model to variations in input parameter related to assumptions made previously. It provides information on which parameters, further study must focus on. The following simulations are done:

- Two simulations investigate change in the yield limit ('sens1' and 'sens2'). In the first all data for the yield limit is raised by 10%. In the latter, the room temperature yield limit is changed to 400MPa (from 250MPa) leaving all other untouched. Since the next data set is given to ANSYS at 400°C (210 MPa) linear interpolation is used for intermediate temperatures.
- Test with a narrower torch ('sens3'). A torch width of 3cm is used instead of the usual 4cm. The maximum temperature is kept constant.
- One test investigates the influence of the plate size on the local plastic deformation ('sens4'). A plate size of 1.5m by 0.75m is used.
- Test the influence of using kinematic hardening instead of isotropic hardening ('sens5').

All the sensitivity calculations are modifications to test No. 14 (T=600°C, h=15mm, $v=10\,{}^{mm}\!/_{s}$). As reference a new simulation, 'sens0', is made similar to test case No. 14—but this time carried out with ANSYS 5.5. Comparing with data for test No. 14 in Appendix A, one can see the difference between the two versions' results.

Table 6: Influence of various parameters on residual plastic strain.

	sens0	Sens1	Sens2	Sens3	Sens4	Sens5
D_x	$-3.25\cdot10^{-4}$	$-3.46\cdot10^{-4}$	$-2.88\cdot10^{-4}$	$-2.18\cdot10^{-4}$	$-3.27\cdot10^{-4}$	$-3.41\cdot10^{-4}$
B_x	$2.05\cdot10^{-4}$	$2.98\cdot10^{-4}$	$3.84\cdot10^{-4}$	$2.51\cdot10^{-4}$	$2.04\cdot10^{-4}$	$2.01\cdot10^{-4}$
D_y	$-2.79\cdot10^{-4}$	$-2.61\cdot10^{-4}$	$-2.20\cdot10^{-4}$	$-1.91\cdot10^{-4}$	$-2.81\cdot10^{-4}$	$-3.02\cdot10^{-4}$
B_y	$4.92\cdot10^{-4}$	$4.87\cdot10^{-4}$	$4.07\cdot10^{-4}$	$3.52\cdot10^{-4}$	$4.94\cdot10^{-4}$	$5.18\cdot10^{-4}$

Table 7: Percentage change from case No. 14 based on table 6.

	Sens1	Sens2	Sens3	Sens4	Sens5
D_x	6%	-11%	-33%	1%	5%
B_x	45%	87%	22%	0%	-2%
D_y	-6%	-21%	-32%	1%	8%
B_y	-1%	-17%	-28%	0%	5%

From these tables one can see, that the bending in the x-direction, B_x, is highly influenced by the yield limit. However, D_x, D_y, and B_y are much less sensitive to those changes. The results not very sensitive to the use of either isotropic or kinematic hardening.

A narrower torch will produce less deflection in general, but with more x-direction bending, B_x. Finding the optimum torch width needs more investigation. The results are moderately sensitive to changes in torch width, why this should be investigated in detail, for example by direct measurements on the temperature distribution on a heated plate.

Finally, the results presented in this paper are actually independent of the plate size.

Conclusion and Recommendations

It is shown that plastic strain data from a thermo-elastic-plastic analysis may be simplified and applied to an elastic analysis with good agreement in results. This saves orders of magnitudes in computing time and may thus be used for an optimisation procedure followed by direct calculations for verification.

Unfortunately, the prediction of the results for yet unknown values of the maximum temperature torch speed and plate thickness was not very successful. The result database should be improved further by recalculation of some of the data being fit by the multivariate analysis.

From the sensitivity analysis, it is shown that more effort must be put into measurements of the actual heat distribution from a gas torch, as this is important to the results. Finally, it must be verified by experiments that the numerical simulations are actually capable of predicting the actual behaviour of the Line Heating process.

Acknowledgement

The correlation analysis and solution of the coefficients with multivariate analysis is carried out with a computer program kindly made available by Jang Hyun Lee of Department of Naval Architecture and Ocean Engineering, Seoul National University.

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Appendix A

Test Programme Details

The table below summarises the parameters used in the 27 test runs that are used for deriving the empirical data. For example, case No. 23 has the properties T_{max} = 700°C, h = 15mm and v = $10\,^{mm}/_{s}$.

Table 8

h	Case No.			v
10	1	10	19	
15	2	11	20	5
20	3	12	21	
10	4	13	22	
15	5	14	23	10
20	6	15	24	
10	7	16	25	
15	8	17	26	15
20	9	18	27	
	500	600	700	

T_{max}

Linearised Deformation Data

In the following table all the linearised deformations are summarised.

Table 9

Case	D_x	B_x	D_y	B_y
1	$-6.31 \cdot 10^{-4}$	$7.31 \cdot 10^{-5}$	$-4.72 \cdot 10^{-4}$	$3.70 \cdot 10^{-4}$
2	$-3.41 \cdot 10^{-4}$	$2.41 \cdot 10^{-4}$	$-2.43 \cdot 10^{-4}$	$3.92 \cdot 10^{-4}$
3	$-2.10 \cdot 10^{-4}$	$2.94 \cdot 10^{-4}$	$-1.78 \cdot 10^{-4}$	$3.10 \cdot 10^{-4}$
4	$-4.92 \cdot 10^{-4}$	$1.32 \cdot 10^{-4}$	$-2.94 \cdot 10^{-4}$	$4.27 \cdot 10^{-4}$
5	$-2.56 \cdot 10^{-4}$	$2.67 \cdot 10^{-4}$	$-1.76 \cdot 10^{-4}$	$3.32 \cdot 10^{-4}$
6	$-1.67 \cdot 10^{-4}$	$2.75 \cdot 10^{-4}$	$-1.38 \cdot 10^{-4}$	$2.55 \cdot 10^{-4}$
7	$-3.71 \cdot 10^{-4}$	$1.36 \cdot 10^{-4}$	$-2.00 \cdot 10^{-4}$	$3.85 \cdot 10^{-4}$
8	$-2.00 \cdot 10^{-4}$	$2.67 \cdot 10^{-4}$	$-1.49 \cdot 10^{-4}$	$2.87 \cdot 10^{-4}$
9	$-1.52 \cdot 10^{-4}$	$2.67 \cdot 10^{-4}$	$-1.20 \cdot 10^{-4}$	$2.30 \cdot 10^{-4}$
10	$-7.22 \cdot 10^{-4}$	$6.41 \cdot 10^{-5}$	$-8.24 \cdot 10^{-4}$	$4.77 \cdot 10^{-4}$
11	$-5.38 \cdot 10^{-4}$	$2.57 \cdot 10^{-4}$	$-4.69 \cdot 10^{-4}$	$6.50 \cdot 10^{-4}$
12	$-3.74 \cdot 10^{-4}$	$3.69 \cdot 10^{-4}$	$-3.56 \cdot 10^{-4}$	$5.81 \cdot 10^{-4}$
13	$-6.24 \cdot 10^{-4}$	$1.10 \cdot 10^{-4}$	$-5.44 \cdot 10^{-4}$	$6.07 \cdot 10^{-4}$
14	$-3.89 \cdot 10^{-4}$	$2.81 \cdot 10^{-4}$	$-3.24 \cdot 10^{-4}$	$5.69 \cdot 10^{-4}$
15	$-2.44 \cdot 10^{-4}$	$3.44 \cdot 10^{-4}$	$-2.32 \cdot 10^{-4}$	$4.11 \cdot 10^{-4}$
16	$-5.09 \cdot 10^{-4}$	$1.35 \cdot 10^{-4}$	$-3.90 \cdot 10^{-4}$	$6.10 \cdot 10^{-4}$
17	$-2.97 \cdot 10^{-4}$	$2.98 \cdot 10^{-4}$	$-2.43 \cdot 10^{-4}$	$4.62 \cdot 10^{-4}$
18	$-2.03 \cdot 10^{-4}$	$3.26 \cdot 10^{-4}$	$-1.87 \cdot 10^{-4}$	$3.40 \cdot 10^{-4}$
19	$-9.20 \cdot 10^{-4}$	$8.64 \cdot 10^{-5}$	$-1.27 \cdot 10^{-3}$	$6.03 \cdot 10^{-4}$
20	$-6.99 \cdot 10^{-4}$	$2.75 \cdot 10^{-4}$	$-7.21 \cdot 10^{-4}$	$8.68 \cdot 10^{-4}$
21	$-4.49 \cdot 10^{-4}$	$3.69 \cdot 10^{-4}$	$-4.88 \cdot 10^{-4}$	$7.64 \cdot 10^{-4}$
22	$-7.58 \cdot 10^{-4}$	$1.38 \cdot 10^{-4}$	$-8.81 \cdot 10^{-4}$	$7.68 \cdot 10^{-4}$
23	$-4.83 \cdot 10^{-4}$	$2.79 \cdot 10^{-4}$	$-4.60 \cdot 10^{-4}$	$7.58 \cdot 10^{-4}$
24	$-3.14 \cdot 10^{-4}$	$3.78 \cdot 10^{-4}$	$-3.15 \cdot 10^{-4}$	$5.60 \cdot 10^{-4}$
25	$-6.18 \cdot 10^{-4}$	$1.56 \cdot 10^{-4}$	$-6.03 \cdot 10^{-4}$	$7.85 \cdot 10^{-4}$
26	$-3.90 \cdot 10^{-4}$	$3.14 \cdot 10^{-4}$	$-3.53 \cdot 10^{-4}$	$6.51 \cdot 10^{-4}$
27	$-2.70 \cdot 10^{-4}$	$3.81 \cdot 10^{-4}$	$-2.73 \cdot 10^{-4}$	$4.91 \cdot 10^{-4}$

AN OBJECT-ORIENTED CONTROL SYSTEM FOR AN AUTOMATED LINE HEATING PROCESS

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Abstract

A control system for an automated line heating process is developed by use of object-oriented methodology. The main function of the control system is to provide real-time heating information to technicians or automated machines. The information includes heating location, torch speed, heating order, and others.

The system development is achieved by following the five steps in the object-oriented procedure. First, requirements are specified and corresponding objects are determined. Then, the analysis, design, and implementation of the proposed system are sequentially carried out.

The system consists of six subsystems, or modules. These are (1) the inference module with an artificial neural network algorithm, (2) the analysis module with the Finite Element Method and kinematics analysis, (3) the data access module to store and retrieve the forming information, (4) the communication module, (5) the display module, and (6) the measurement module.

The system is useful, irrespective of the heating sources, i.e. flame/gas, laser, or high-frequency induction heating. A newly developed automated line heating machine is connected to the proposed system. Experiments and discussions follow.

Introduction

Line heating is a method used in the production of curved shells at the bow and stern of a ship. The process is generally regarded as one of the outdated technologies in the modernized and automated shipbuilding process. Only a few chief technicians at a shipyard are able to provide limited heating information, which is based on their long experience. Other workers simply apply heat to a plate along lines, as requested by the chief technicians. No reliable data can be obtained from shipyards, since measurement of input and output quantities is not practical. Basic questions may arise as to which quantities should be measured in order to use them in succeeding jobs.

Since the line heating has been introduced, numerous studies have concentrated on how to determine the heating paths. In practice, the heating paths are determined in an obscure manner by skillful workers. Thermo-elastic-plastic mechanics [Moshaiov and Shin 1992], geometry analysis [Letcher 1993] [Yoo et al. 1995] [Ryu 1998], finite element methods [Shin et al. 1995], inherent strain concepts [Ueda et al. 1994] [Chang and Moon 1998], as well as other approaches have been applied to the understanding of line heating. Most have commented on the automation of line heating in their research on heating paths. However, in order to achieve the automation of line heating, a control system needs to be developed. The system should be able to integrate the large amount of forming information and to create a seamless data flow. In addition, it should be easily updated or revised as the relevant technology improves.

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The objective of this paper is to develop a control system for an automated line heating process. Object-oriented methodology is employed to develop the system efficiently. The methodology can be useful for the development of a system having large data, complex information flow, and which requires frequent revisions. The major concept on the automated process is presented, followed by methodology and implementation. For verification of the system, a corresponding machine has been designed and tested. Since the system produces the forming information, it can be useful for individual workers as well as for any automated line heating machine.

Current Line Heating Process

In shipyards, the current process has already been investigated in [AESA 1992]. The process is almost the same in most shipyards in the world. Figure 1 shows the current line heating shop in a shipyard.

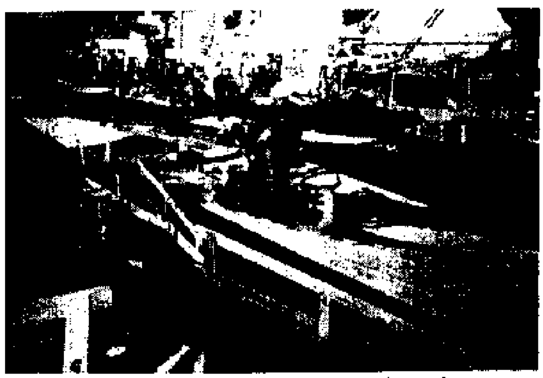

Figure 1: A typical line heating shop

The shop is very hot and noisy. A set of several wooden or recycled-paper templates per each plate are used as tools for checking the surface of a formed plate. The templates are discarded after checking a plate piece. Heating paths are drawn by one of the chief technicians. The paths are the result of the experience and intuition of an expert. It is said that at least several years' experience is required for a technician to draw heating lines with confidence. In addition, in the middle of the formation process, the templates do not exactly match the surface of a plate. The workers then determine the new heating paths by qualitative differences between the templates and the plate. In conclusion, every information in the line heating shop is not quantified, nor computerized.

Based on the shipyard practices, the information flow of the current forming process is illustrated in Figure 2. It can be seen that the design and production processes are separate in terms of information and participating personnel. Usually the design is carried out by engineers, while the actual production by technicians.

To overcome this, a new automated line heating process would be desireable. The process should be based on quantitative heating information, compared to the qualitative one in current shipyard practice. The information is not only concerned with heating paths but also others, such as torch speed, cooling, and torch height. For example, a heating path is determined by coordinates of two ends. All data should be stored in a computer so that it can be used in the next job. Since there is considerable data, the relation of which is very complicated, a systematic approach is inevitable in the development of a control system of the new process.

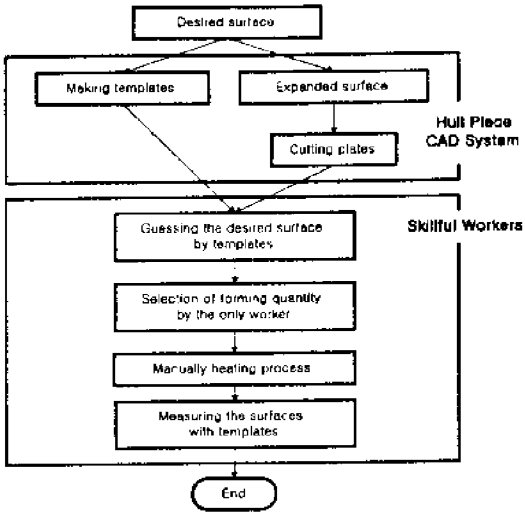

Figure 2: The current line heating process

An Object-Oriented Control System for an Automated Line Heating Process

In order to develop the control system for an automated line heating process, object-oriented technology is employed in this paper. The five steps in object-oriented technology, shown in Figure 3, are system requirements, selection of system objects, analysis, design, and implementation of the system.

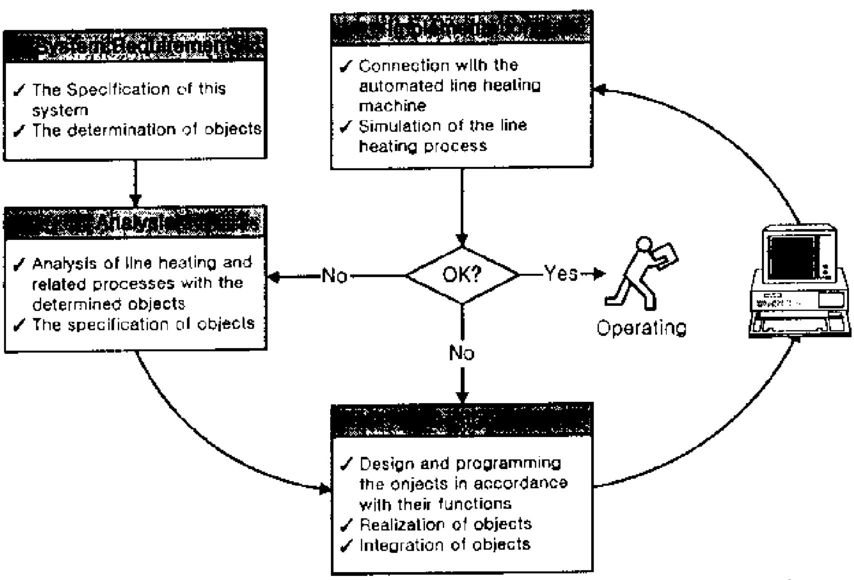

Figure 3: Developing steps of a control system for an automated line heating process

In the system requirement step, the automated line heating process is identified in detail. The objects of the machine and the control system are then determined. In the analysis step, the line heating process and the related processes are analyzed with the objects. At this point, the specifications of each object are determined with attributes (or data) and methods (or functions). In the design step, the objects are designed and programmed corresponding to their functions. The objects are realized by use of proper developing tools in this step, following which they are integrated into a single system. In the implementation step, the developed control system is connected with the virtual machine and the hull forming process, i.e. the line heating is simulated with this integrated line heating system. For the sake of convenience, the control system is referred to as 'KOJEDO', which is a Korean acronym for 'an assistant to the formation of hull pieces.' Internationally, Koje island, or Koje-Do of Korea, is known as one of modern shipbuilding complexes. The details of each step are as follows.

System Requirement and Determination of System Objects

The system requirements are specified and the modules of this system are determined in this step. The new automated line heating process should be computer-controlled in order to:

- serve as input for the computerized data
- form the hull pieces with high accuracy,
- reduce man-hours required
- automatically generate the process planning in real time or in the off-line program
- manage this workshop in the integrated manufacturing system with other workshops and the information system.

The system objects are determined after focusing on the above requirements. Those are classified into two categories with six subsystems. The line heating process in Figure 4 shows the six modules and their basic relations.

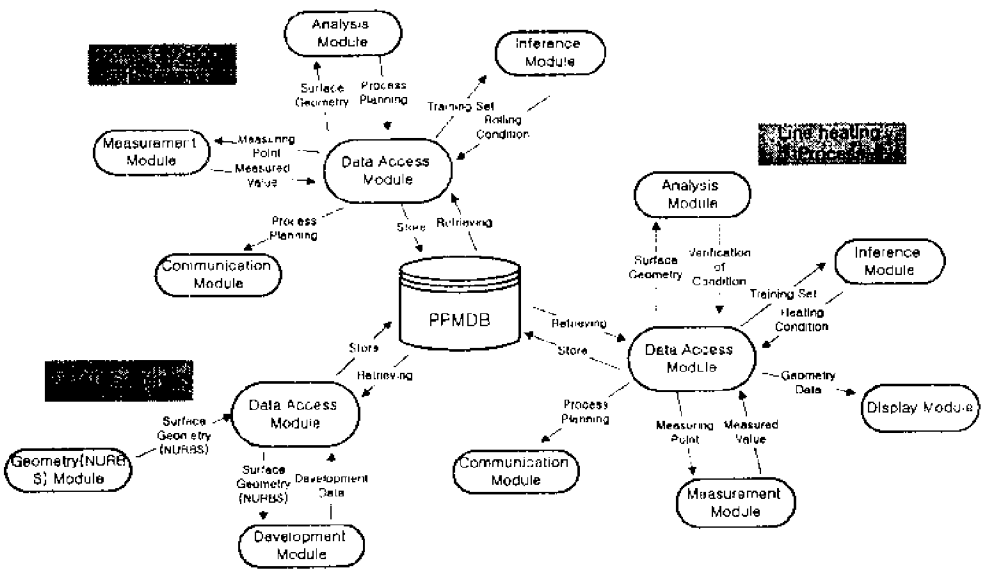

Figure 4: Global information flow and the objects in the hull forming system

The first category is the process information system which consists of the following three subsystems, or modules.

① Analysis module with use of Finite Element Method (FEM) and kinematic analysis.

② Inference module with an artificial neural network algorithm (ANN).

③ Data access module with the product database

The second category is the process control system which consists of the following three modules.

④ Measurement module with measuring hardware

⑤ Communication module with the machine and other workshops

⑥ Display module with the computer monitor and printers

Following the approach by Schenck and Wilson [1994], basic objects for our system are defined as follows.

Hull Piece, Kinematics, Bending Strain, In-plane Strain, Piece-forming Method, Rolling, Line heating, Rolling Condition, Heating Condition, Material Property, NURBS Surface, Offset Table, ANN Model

Next, all analysis and design are carried out on the line heating process and the adjacent processes with these modules.

Analysis and Design of the Line Heating Process and the Related Processes

In this step, the subsystems of the line heating process are analyzed together with the adjacent manufacturing processes. Figure 4 shows the subsystems and the information flow with the adjacent processes. The Computer-Aided Design (CAD) process for the geometry of curved plates and the shell development is included. In addition, the roller bending process to obtain the cylindrical shells is included, since the rolling process is the pre-forming stage for line heating. These constitute the parts in the entire hull forming fabrication, that is, production design, cutting, roller forming, and line heating.

Each process requires input and output data, which are essential in the determination of the processing information and for the control of the forming process. For example, these are the geometry of an objective curved shell, forming conditions, and the measured data. The automated line heating process can obtain the geometry of the objective curved shell and its developed shape from the CAD system, and should obtain the measured data of the initially rolled plate from the roller bending process.

The six subsystems of the control system have their attributes and methods on the basis of such data in the line heating. The attributes and methods of each subsystem are shown in Figure 5. The functions of subsystems are summarized, along with their attributes.

1. <u>Analysis module</u>: to simulate line heating with the given conditions using the external FEM packages [Shin et al. 1995] and to obtain the curvatures of the curved shell, the strains, and the heating paths from the kinematic analysis [Ryu 1998].

2. <u>Inference module</u>: to provide the forming input value, i.e. the heat quantity, torch gap, heating speed, gas pressure, and the like, by using ANN [Park et al. 1997] and the experimental formula [Lee 1999].

3. <u>Data access module</u>: responsible for saving the implemented results into a database and retrieving the data by an application program corresponding to each access format. This includes the access to the Plate Product Model Database (PPMDB) and the packing of the data that are required by each module.

4. <u>Measurement module</u>: to sort the measuring points, to send them to the measurement device and to obtain the results after measuring the formed plates.

5. <u>Communication module</u>: to transmit processing commands, information and status through machines and the other forming workshops. In choosing two physically separated computer's communication regulation, a standard communication regulation, or communication module is appropriate. When the control system is some difference from the machine, this module enables the main control system to operate the remote machine.

6. <u>Display module</u>: to output the progress of calculation and processing to monitors and printers in a user-friendly manner.

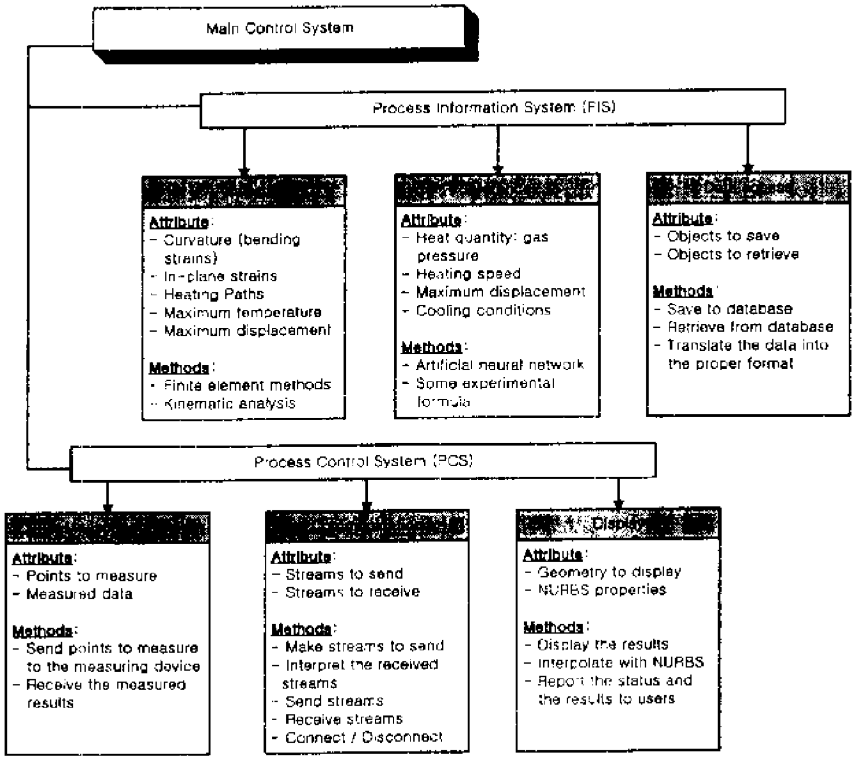

Figure 5: The attributes and the methods of each subsystem

Among data in each module and each process, persistent data must be stored in the database. For the automation of hull forming process, the processes and the data flow between them must be known. These constitute the basis of the product data model and is referred to here as the PPMDB(Plate Product Model DataBase). All persistent data used in overall system arises from the PPMDB. The measured data after forming and the forming conditions are stored in the PPMDB. In addition, for the case where the data are given in STEP (Standard for the Exchange of Product model data) file formats, the STEP file is available. The STEP formats are of two types: one is for the modeling of the products and the other for the production information

Integration of the six objects can lead to the development of a control system for the new automated line heating process, as illustrated in Figure 6. The control system computes the processing information with curvatures and strains, and connects other modules of system. The curvatures and strains are calculated from kinematic analysis [Shin and Kim 1997]. Using the results, the information on heating paths of line heating [Ryu 1998] and on rolling process also can be obtained. The calculated data is input to the inference module and the display module, and the processing information is transmitted to the machine or technicians through the communication module. The measured points, torch speeds, and paths are controlled through the measurement module. All information is stored in the PPMDB through the data access module.

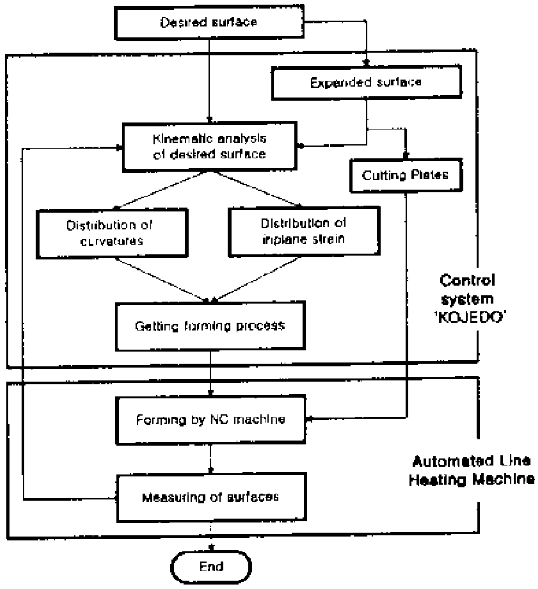

Figure 6: The new process for an automatic line heating

Implementation of the Control System

Based on the new automated line heating system, as shown in Figure 6, the control system is realized by implementing the objects. In this step, a virtual machine is developed instead of an actual machine for modifing an accurate calculation and to provide smoothly flowing information. Since this virtual machine cannot actually measure the curved shell, the measured displacement is generated with some assumptions. Figure 7 shows the template of the developed control system KOJEDO into which the six subsystems have been integrated. This virtual machine and the system can be used as an off-line teaching or programming tool. In this paper, EXPRESS and EXPRESS-G are used as lexical and graphical representation methods.

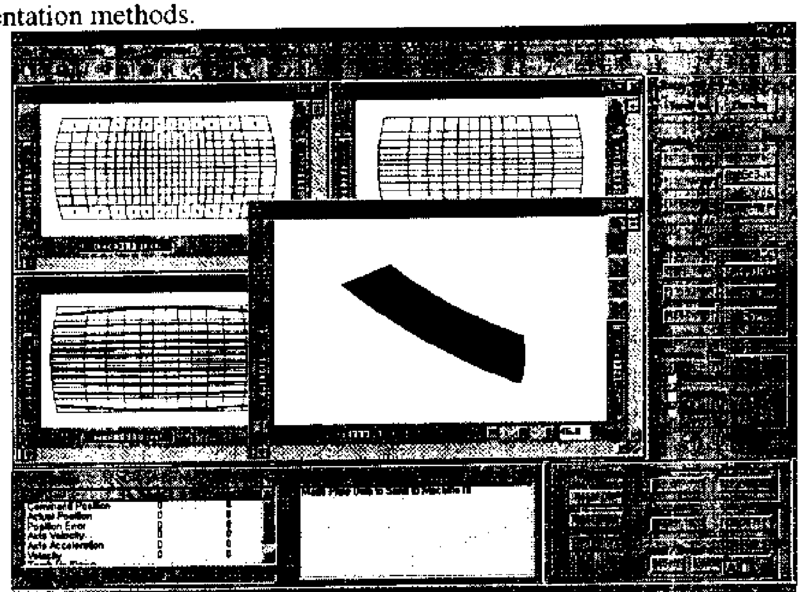

Figure 7: The KOJEDO system template for the automated line heating process

An Computerized and Automated Line Heating Machine

According to the proposed concept of the automated line heating process, an automatic line heating machine is developed, as shown in Figure 8. The machine, called *i*CALM (Intelligent Computerized and Automated Line heating Machine), is based on PC–NC (personal computer operated-numerically controlled) logic. It contains the heating and cooling unit, a measuring unit, a communication unit, a control PC, and others. The control system, developed in this paper, is installed in the machine to automate the process.

Figure 8: An automated line heating machine, *i*CALM, and experimental setup

Test of the System and Verification Example

A simple model was tested with this simulator. The simulation model is expressed in the following parametric mathematical form.

$$S(u,v) = \left(a\frac{2u(1-v^2)}{(1+u^2)(1+v^2)}, b\frac{2v(1-u^2)}{(1+u^2)(1+v^2)}, c\frac{(1-u^2)(1-v^2)}{(1+u^2)(1+v^2)} \right)$$

$$a = 500, b = 300, c = 200, \ -0.2 \le u,v \le 0.2$$

This model is one of the quadratic surfaces and is called the ellipsoid. The shape is shown in Figure 9.

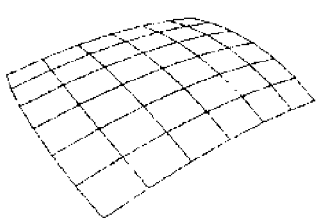

Figure 9: The shape of the simulation model

In the analysis module, the primary heating paths for transverse bending are obtained as shown in Figure 10.

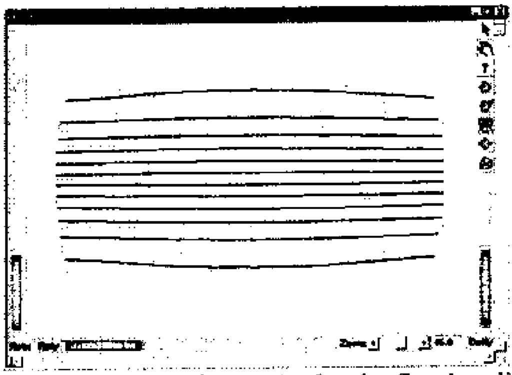

Figure 10: The heating paths for the first bending

After measuring the formed surface through the measurement module, the secondary heating paths for the longitudinal bending are calculated as shown in Figure 11. It is not the concern of this paper whether the heating paths are exact or not. The main goal is to develop an integrated system for the automated line heating process.

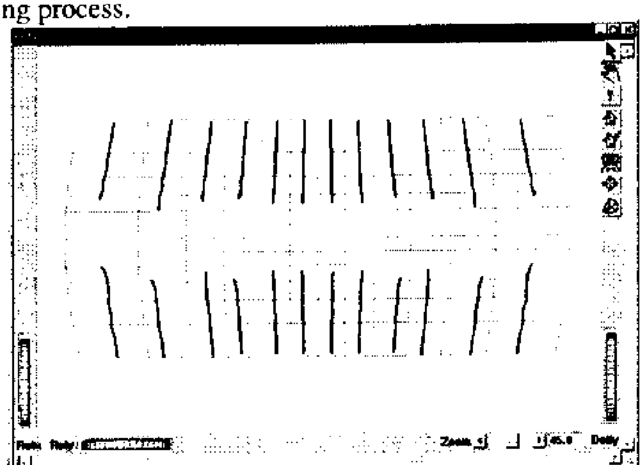

Figure 11: The heating paths for the longitudinal bending

Conclusions

In this paper, a prototype control system is proposed for an automated line heating process. In addition, an automatic line heating machine is developed, in order to make the system complete.

Since the amount of data is huge and the information flow is very complex, object-oriented methodology is employed for developing the system. By following the development steps of the methodology, a new automated process is realized. The proposed, automated system is compared with the current, experience-dependent system. The proposed control system consists of six subsystems: the analysis, the inference, the data access, the communication, the measurement, and the display module. A product data model is constructed to store and retrieve all data in the automated process. By using the development system, data are accumulated in such a manner that highly precise forming conditions can be obtained.

This system is useful, irrespectively of heating methods, i.e. flame/gas, laser, or high frequency induction heating. In addition, the generated information is quantified, and thus useful for both technicians as well as other automated machines.

However, the automation system in this paper is not connected to the other systems, such as the design system, the roller bending system, and the process control system. This results in a problem of 'islands of automation' which are found in most shipbuilding processes. If these connections are considered in the future, the automation system suggested in this paper could be used more efficiently.

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A FINITE ELEMENT MODEL FOR METAL FORMING BY LASER LINE HEATING

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Abstract

Line heating is an efficient method of forming doubly curved plates and shells. The controllability and stability of the laser beam make it an ideal source for automation. This paper summarizes part of the research work at MIT on metal plate forming by laser line heating. Three dimensional finite element method (FEM) was employed in the analysis of the forming process. A rezoning technique was applied to reduce computation time while capture the characteristics of the laser forming process. By using this model, we simulated the laser forming process and obtained results consistent with those obtained in experiments. A parametric study of edge effects and laser heat input was also performed. The numerical results are consistent with experimental observations.

1 Introduction

Metal forming happens when a metal plate is subjected to stresses larger than the yield stress so deformation goes beyond elastic range. Two mechanisms are commonly used to form steel plates into curved shells, *mechanical forming* and *thermo-mechanical forming*. In mechanical forming, an initially flat metal plate is pressed to a die of proper shape, or is fed to a set of rolls to produce the plastic deformation required to produce the design shape. In thermo-mechanical forming, plastic deformation is produced by heating and then cooling the metal plate. When a plate is heated at one side while the other side is kept cool, the temperature gradient across the thickness of the plate generates different expansion acorss the thickness of the metal plate, thereby causing the plate to bend. Since the temperature is high and the yield stress of the metal is low in the region directly under the heat source, plastic deformation occurs. After the plate cools down, as a result of compressive plastic strains, the heated area shrinks, causing the plate to bend reversely. Line heating by an oxyacetylene torch is a commonly used method for thermo-mechanical forming, especially in shipyards. Another method is laser forming, where a laser beam is used as the heat source. Essentially, the mechanism of laser forming is the same as that of forming by an oxyacetylene torch. The advantage of using a laser beam over an oxyacetylene torch is that the heated area is more focused and easier to control and repeat.

Forming by flame or laser line heating has been an active research topic in manufacturing, especially in shipbuilding [3, 16, 9]. Research on the mechanism of the line heating process [13, 15, 19, 14, 5] aims to predict the final shape of the metal plate when given the heating conditions and mechanical properties of the metal plate to be heated. Finite element method (FEM) or simplified beam or plate theory is usually applied. Research on design of the proper heating and cooling processes [23, 24, 25, 22] is based on the experience on forming simple shape surfaces from rectangular plates. No general process planning scheme for general curved shapes nor automatic control of the forming process is available. Therefore, current state-of-the-art laser forming procedures are far from automatic.

From 1996 to 1998, Defense Advanced Research Program Agency (DARPA) funded a 3-year project on "Laser Forming for Flexible Fabrication" [26]. The research teams consisted of Boeing Company, Massachusetts Institute of Technology, Native American Technologies Company, Newport News Shipbuilding Company, and Pennsylvania State University. The activities the MIT research team has been involved include (1) development of a process design algorithm for laser forming [10, 18], (2) development of a finite element model to predict the metal displacement during heating process and the resulting out-of-plane distortion [6, 7, 4, 12, 11]. This paper reflects the second activity and is organized as follows: Section 2 presents the FEM model, while Section 3 verifies the model by comparing the numerical results with experimental results. Section 4 presents the results from a parametric study. Finally, Section 5 concludes the paper.

2 Finite Element Model for Laser Line Heating

The problem of bending metal plates by line heating can be divided into two sub-problems: the heat conduction/transfer problem and the elastic-plastic deformation problem, where the solution of the first problem is a prerequisite of the second problem. According to the mechanism of laser forming process, we have developed a finite element model for thermal and mechanical analysis of this process. The ABAQUS^{TM} software is used for finite element analysis.

2.1 Rezoning Technique for Laser Forming Analysis

The process of shell forming by line heating is a coupled nonlinear thermo-mechanical process, which makes the complete simulation difficult. Numerical simulations of line heating process such as FEM analysis have achieved some success in predicting the final state of distortion, but the computation time is typically very long (in the order of days) which makes FEM not suitable for real-time analysis. During the shell forming process, the heat source moves and only the area which is very near the heat s/ource undergoes large amount of heat transfer and plastic strains. The remaining areas have small changes of temperature and small amount of stresses and strains, which imply that a sparse mesh in these areas is sufficient. The ordinary FEM analysis, which uses a uniform fine mesh along the entire heating line greatly increases the number of degrees of freedoms, making the analysis slow. In order to obtain convergent and highly accurate results in a reasonable time, we use a 3D rezoning technique in the FEM simulations of laser forming process. This involves remeshing of the metal plate so that the area directly under the laser beam has a denser mesh while other areas have sparser meshes (see Figures 2 and 3 for an illustration).

The plates formed by line heating are usually treated as thick plates, since it is the gradient of the temperature across the thickness that provides the mechanism to bend these plates. Therefore, 3D FEM analysis is necessary and a 3D mesh needs to be generated. For our research, 8-node brick elements and 6-node triangular prism elements are the two types of elements used in analysis.

An algorithm has been developed to generate rezoning meshes for rectangular plates. It reads the necessary information for the mesh to be generated from an input file, and the output file from the thermal and mechanical analysis in the previous step (if any), then generates the input file for analysis in the next step. The basic procedures of this mesh generation code are:

1. Generate dense grid for the planar area of one side of the plate surface.
2. Generate previous mesh, i.e., get the correspondence between the grid points and the node points of the previous mesh.
3. Read the node temperatures (from the output file of the thermal analysis of the previous step) or the elemental stresses at each node (from the output file of the mechanical analysis of the previous step) and interpolate this data at the grid points.

4. Pick up the corresponding grid points and generate new mesh in 2D according to the input file.
5. Take the offset of planar mesh in the direction of the plate thickness and generate 3D mesh. The thickness of layers increases across the thickness of the plate, being fine near the heated side.
6. Write the node coordinates, element formation for the 3D mesh. and the information of convection/radiation faces corresponding to the elements at the surface.
7. Obtain the initial temperature at each node (for thermal analysis) or the initial stresses in each element (for mechanical analysis) for the new mesh according to the node and grid point correspondence.
8. Generate input files for thermal and mechanical analysis for the new mesh.

2.2 Thermal Boundary Condition

Boundary heat transfer is modeled by natural heat convection and radiation. Convection follows Newton's law, where the coefficient of convective heat transfer is a function of the temperature difference between the boundary and the environment and of the orientation of the boundary [20]. The rate of heat loss due to radiation is proportional to the difference between the fourth power of the temperature of the boundary and that of the environment. The surface emissivity is taken to be constant.

2.3 Spatial Distribution of Heat Flux

Heat flux from an oxyacetylene torch or a laser beam is usually modelled as Gaussian distribution [21]. In this project, according to measurements by researchers at the Applied Research Laboratory of Pennsylvania State University [26], the distribution of heat input is modelled as a truncated Gaussian distribution involving a Gaussian distribution in an inner region and a uniform distribution in an outer annular region. About 70% of the total energy is in the inner region. The diameter of the inner region is the spot size d_h, and the diameter of the entire heated region is about $d_o=2d_h$.

2.4 Material Properties of Mild Steel Plates

Material properties such as density, thermal conductivity, specific heat, Young's modulus of the mild steel plates used during the experiments are obtained from [1][2]. These properties are all temperature dependent. At high temperatures, Young's modulus and yield stress are given small, finite values to avoid difficulties with numerical convergence [1].

2.5 Mechanical Boundary Conditions

In mechanical analysis, necessary constraints are added to eliminate rigid body movement, according to the fixtures used in real experiments, with which comparison is meaningful.

3 Verification of the FEM Model

We have verified our model by comparing the numerical results we obtained from our simulation with experimental results. The experiments were performed on 0.3048m × 0.3048m × 0.0254m mild steel plates with heating lines at various distances from the edge. The power of the laser is 2.6 kW. We used the results from the experiments when the heating line was 0.1143m from the edge. The plates were clamped at two points during experiments (see Figure 1). The vertical displacements at 5 points were measured. The experimental setup is shown in Figure 1, where d_1=0.0254m, d_2=0.0635m,

d_3=0.0381m, d_4=0.1143m. We performed detailed thermo-mechanical analysis for two cases: (1) Heat source moving velocity 7.62 cm/min; and, (2) heat source moving velocity 9.652 cm/min.

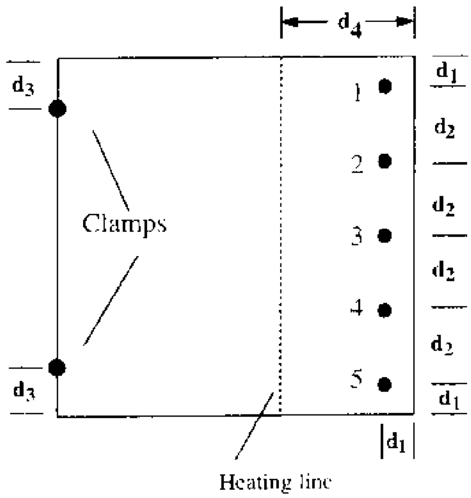

Figure 1: Heating pattern and measuring points in mild steel experiments

Experimental results for these two cases were obtained from the research team at Pennsylvania State University [26]. An absorption rate of 60% was used during numerical simulation based on our experience. The rezoning meshes for the first two steps are shown in Figure 2 and Figure 3. By using the rezoning technique, computation time was reduced significantly. After the numerical simulation was complete, the displacements at the measuring points in Figure 1 were interpolated from those at the FEM nodes. The comparisons between the numerical and experimental results are shown in Tables 1 and 2. Error is the relative error with respect to experimental results. We see that almost all the numerical results are within 15% of the experimental results (the error of 27.9% in Table 1 is probably due to measurement error). This shows the effectiveness of our FEM model. Figure 4 shows the deformed geometry for case 1.

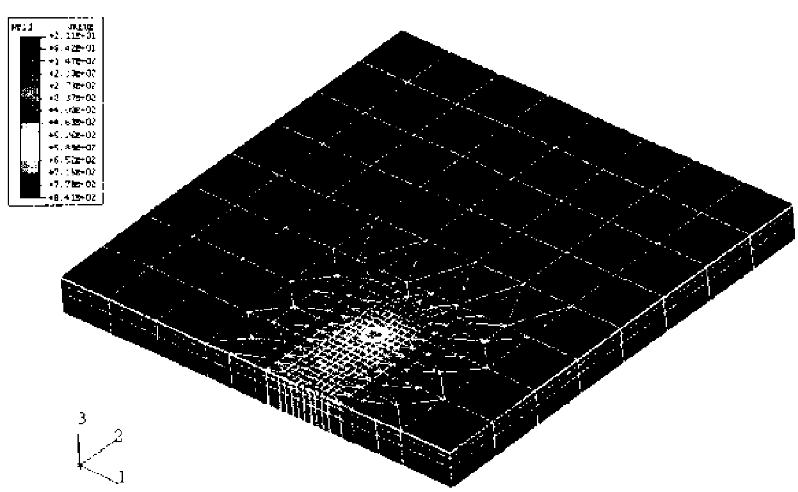

Figure 2: Mesh and temperature distribution at rezoning step 1

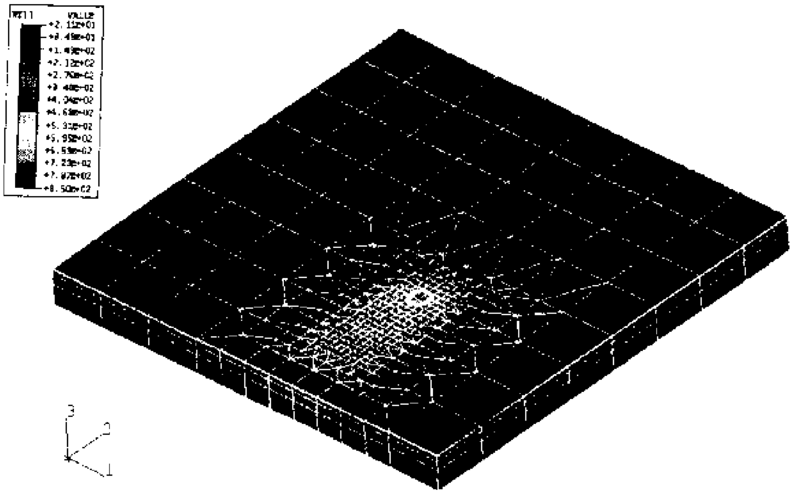

Figure 3: Mesh and temperature distribution at rezoning step 2

Table 1: Comparison of numerical and experimental displacement for case 1

Measuring point	1	2	3	4	5
Numerical displacement (cm)	0.03115	0.02767	0.02626	0.02746	0.03052
Experimental displacement (cm)	0.03556	0.03175	0.02921	0.03810	0.03429
Error (%)	12.4	12.9	10.1	27.9	11.0

Table 2: Comparison of numerical and experimental displacement for case 2

Measuring point	1	2	3	4	5
Numerical displacement (cm)	0.02758	0.02416	0.02096	0.02199	0.02718
Experimental displacement (cm)	0.03226	0.02667	0.02286	0.02413	0.03175
Error (%)	14.5	9.4	8.3	8.9	14.4

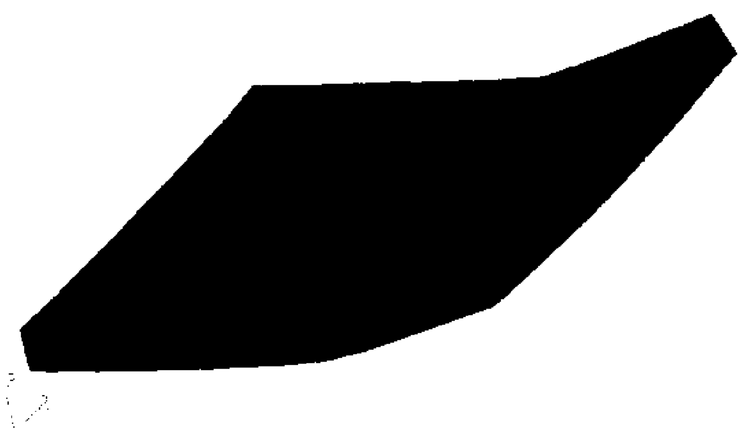

Figure 4: Deformed geometry of the plate due to line heating for case 1

4 Parametric Study

4.1 Edge Effects

In the earlier experimental study [8], it was observed that a laser line heat pass creates less bending as it approaches a free edge. We investigated this phenomenon by numerical simulations. Four heating lines at locations $\frac{3}{8}$L, $\frac{1}{4}$L, $\frac{1}{8}$L, and $\frac{1}{16}$L from the free edge were simulated, where L is the edge length of the plate, L=30.48 cm. The heat source moving velocity is 7.62 cm/min; the power of the laser is 2.6 kW; and the heat absorption rate is 60% for all cases.

After thermo-mechanical analyses, the bending angles for various locations of the heating lines are computed by averaging the bending angles at cross sections passing through points A, B, and C, see Figure 5. The results are shown in Table 3 and Figure 6. These results are in good agreement with the experimental observations, i.e. it is more difficult to bend a plate by heating it near the edge than in the middle area.

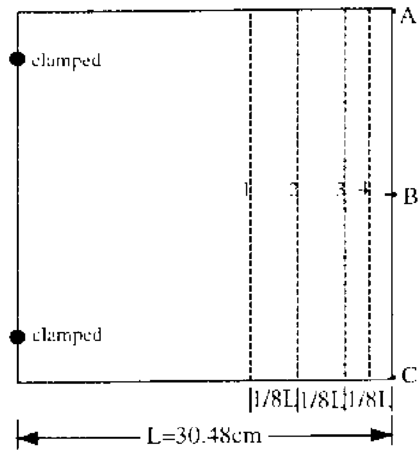

Figure 5: Heating lines for analysis of edge effects

Table 3: Average bending angles when heating at various locations

Heating line Number	1	2	3	4
Distance to edge/edge length	3/8	1/4	1/8	1/16
Bending angle (degrees)	0.1742	0.1746	0.1310	0.06116

4.2 Parametric Study of Heat Input

In this section, we present the results of a parametric study of the effects of heat input on the angular distortion. We performed numerical simulations of laser line heating of a mild steel plate of size 0.3048m × 0.3048m × 0.00635m along its centerline. Compared to the plate used in Section 3 and Section 4.1, a reduced plate thickness was used here to save simulation time. The plate was assumed to deform freely, so we only did simulation on half of the plate due to symmetry condition. The power of the laser was the same as that used in the previous section. We used the following absorption rates: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.625, 0.65, 0.7, 0.8 during thermo-mechanical analysis. Here static meshes were employed in all the analyses because the simulation time was short due to small thickness. The meshes and temperature distributions are shown in Figure 7 for absorption rate of 0.5. A typical deformed geometry is shown in Figure 8, and the computed angular distortions are shown in Table 4 and Figure 9. The results are in general agreement with prior experimental observations [8]. That is, there is an optimal heat input, which generates the maximal bending angle.

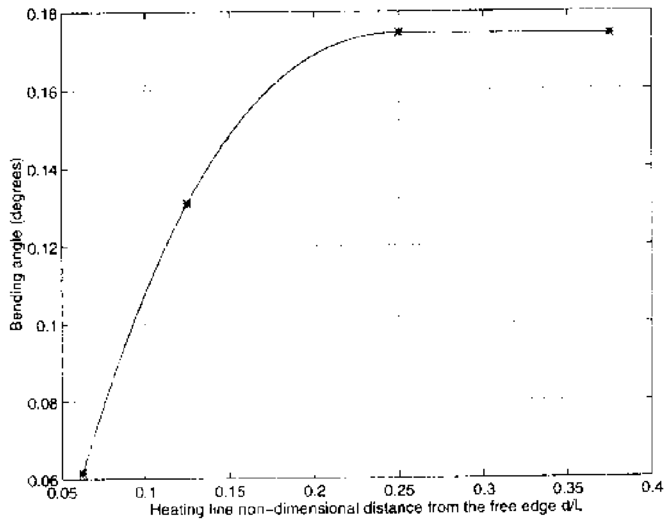

Figure 6: Edge effect -- bending angle as a function of heating line distance from edge

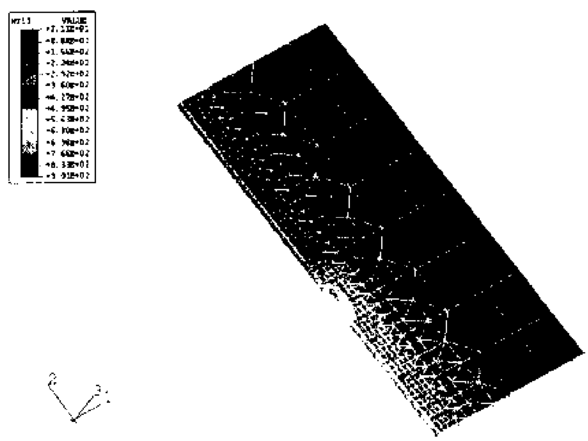

Figure 7: Mesh and temperature distribution for heat input rate 50%

Table 4: Bending angles under various heat absorption rates

Heat absorption rate	0.1	0.2	0.3	0.4	0.5	0.6	0.625	0.65	0.7	0.8
Bending angle (degrees)	4.44e-6	0.0150	0.0662	0.101	0.119	0.137	0.124	0.106	0.0633	0.0435

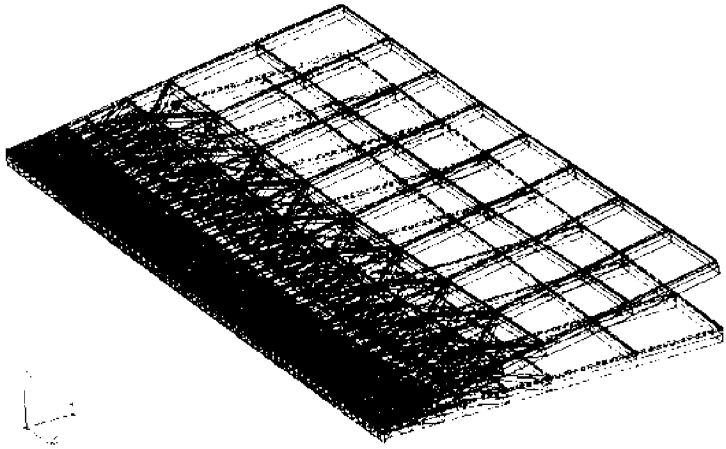

Figure 8: A typical plate geometry after line heating

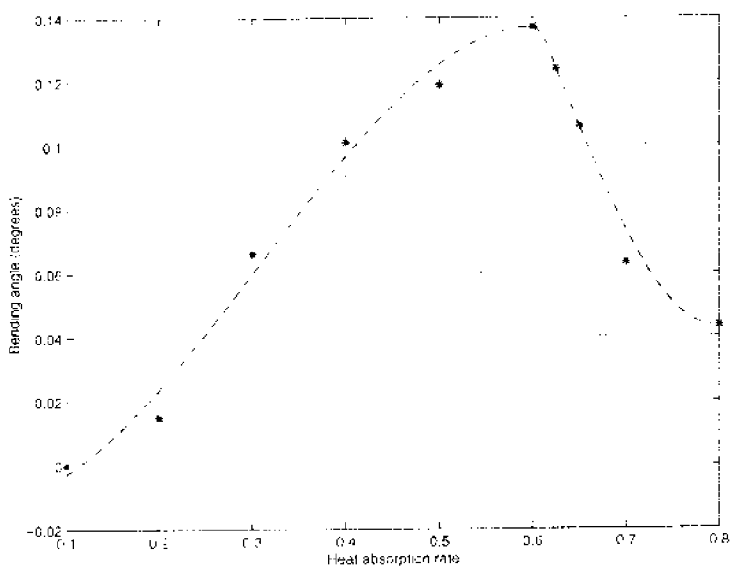

Figure 9: Bending angle as a function of heat absorption rate

As pointed out in Section 1, it is the gradient of the temperature field across the plate thickness that provides the mechanism of plate bending. The temperature field for an infinitely large plate of finite thickness without heat loss due to convection or radiation was first studied by Rosenthal [17]. Under these conditions, the temperature field is proportional to the heat input, which means that the temperature gradient and thus the bending angle, are all proportional to the heat input. This is partially true for our simulations. We see from Figure 9 that the bending angle first increases with the increase of the heat input.

When the heat input becomes larger, the heat loss due to radiation and convection becomes more important, and the temperature field is no longer proportional to the heat input. In fact, because the radiation heat loss is proportional to the fourth power of temperature, heat loss is more significant on the hotter surface than on the cooler surface. Thus the temperature gradient may indeed decrease with the increase of heat input, when the heat input is very large. This is the reason why we see in Figure 9 that the bending angle decreases with the increase of the heat input at high heat absorption rates.

5 Conclusion

This paper presents a finite element model for thermo-mechanical analysis of the process of metal plate forming by laser line heating. Rezoning technique has been employed to reduce the simulation time yet preserve the required accuracy. Comparison of the numerical results with the experimental ones shows the effectiveness of the model.

Acknowledgements

Funding for this research was obtained in part from a DARPA research project in a subcontract from Rocketdyne Division of Boeing North American, Inc. (AF contract No. F33615-95-C-5542) and from the MIT Department of Ocean Engineering. We would like to thank Mr. John Wooten for his assistance throughout the DARPA project, and the research team led by Dr. Richard Martukanitz at Pennsylvania State University Applied Research Laboratory for sharing the results of their experiments.

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An Automatic System for Line Heat Bending Processing Method Utilizing FEM Application

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Abstract

Ishikawajima-Harima Heavy Industries Co., Ltd.(IHI) have accomplished to employ the logic of the Finite Element Method on the principle of Thermal Forming or Line Heating, which facilitates use of computer aided, fully automated line heating machine for forming any curvature precisely and efficiently on a hull steel plate in shipbuilding process.

It is undesirable for the future in line heating that only an experienced technician is able to be skilled in the use of existing line heating for steel plate forming. Accuracy of shape formed by existing line heating is not necessarily well controlled and work of succeeding stages is adversely affected by inaccurate interim products, though it is very useful method in forming steel plates and all apparatus required for line heating is just light tools. IHI-Advanced Line-heating Process for Hull-steel Assembly(IHI-ALPHA) have succeeded to solve these problems.

1. Introduction

Three dimensional curved surface of the outer shell of a vessel, as shown in Figure 1, is processed by means of line heating. Through operation of expansion and contraction under stress from surrounding area and resulting at heated spots which are created by mobile heat source, large plastic strain is obtained in the end.

Numerous efforts are being made in the past four decades to interpret line heating in technical terms in order to automate the process. Some attempted to replace the process by cold work using universal press, and others offered to substitute selected human skills by artificial intelligence technology.

Because the deformation mechanism is so complex that any practical quantification could not be defined, except for occasional support tools such as NC heating device to execute heating plans assumed by experienced craftsmen, few comprehensive efforts to automate the entire process existed.

We applied FEM analysis technology toward full automation of the process, and the resulting system has been implemented at Kure Shipyard of IHI since 1998.

Figure 1 Conventional operation of line heating

Distinctive features of our approach include the following.

- A theory of calculation for the heating plan (a processing instruction of heating method to induce intended curved surface) by use of numerical analysis technique has been established. In dealing with line heating where temperature range is lower compared to, say, welding, thermoelastic-plastic phenomena in question may be treated as inherent strain which can be explained in terms of elastic analysis. Using this nature also makes inverse problem resolution possible, in which to seek required heating plan from the targeted 3-D surface.(1,2)
- It develops the targeted curved surface under condition of minimum dynamic strain energy via FEM simulation. It would perfectly agree with the contraction deformation during thermal bend processing, and insure processing precision particularly within the surface area.
- High frequency induction heating is selected as the heat source, which is simple to control, has excellent reproducibility, and attains desired effect in much shorter time compared to gas burners.

2. Structure of the Theory

The calculation system for heating conditions herein described is to obtain a desired configuration by selecting combination of heat and transformation stored in a data base. The procedure may be divided in two phases, first of which is to establish a strain distribution over the steel plate to be worked (which for the purpose of our system called the required inherent strain), and the second of which is a process of determining heating line arrangement by choosing combination of heating conditions from the data base that would produce commensurate strain distribution with the targeted configuration.

Some of the steps we have taken to verify the validity of the system is described in the following sections.

2.1 Data Base of Heat-Deformation Relationship

Characteristic deformation of heated steel plates is determined by the attribute of heat source and physical property of the heated steel plates, and varies with the changes in temperature distribution, degree of restraint from the surrounding area and of residual stress in the periphery of heated spot, and other external force. In our study which aims at practical use, the heat source is restricted to a specific guided heat device, whereupon each variable factor is linked to relevant process unit, whose effect is then quantified upon experiment using small samples and FEM analysis.

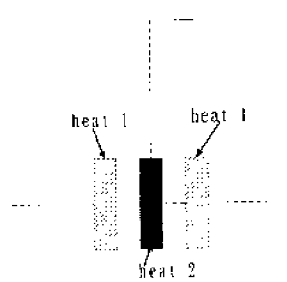


Figure 2 Test piece for parallel heating

Table 1. Deformation obtained by parallel heating experimental

	Apparent deflection		Deflection after severed from sample plate	
	δ m	δ b	δ m	δ b
Heat 1	-0.137	-0.070	-0.162	-0.107
Heat 2	+0.206	+0.122	+0.178	+0.123

The study enabled highly precise estimation of inherent deformation and inherent strain. Part of estimation procedure will be seen in the following examples.

(1) Effect of residual stress from adjacent parallel heating line

Heating to induce inplane contraction of steel plates frequently consists of short heating lines. This often cause unsatisfactory deformation when the heating is applied close to previous heating line.

Figure 2 demonstrates the interference from the short and parallel heating lines to an additional heating line. First two(2) heating lines (called the primary heating) had a distance of 140mm between them. Heating condition was at 37kW for 15 sec. Subsequently, the center of the first two lines was heated on the same condition. (The latter is called the secondary heating.) Table 1 illustrate the resulted deformation. It shows two kinds of data, one of which is indicate apparent deformation of the undisturbed experimented sample as measured after the heating, and the other shows measurement after the heated area is severed from the sample steel plate thus becoming relieved from the residual stress in containing area. In the diagram, - indicates contraction while + shows elongation in deformation. As is obvious from the table, secondary heating caused elongation both in terms of inplane deformation (δ m) and bend deformation (δ b), contrary to the intended purpose of heating.

To interpret the phenomena, an elasticity simulation has been run.(3) As the initial condition, a inherent strain equivalent to one existing in the primary heating area is given, and the Young's modulus is kept sufficiently small. These will simulate temperature rise during the secondary heating.

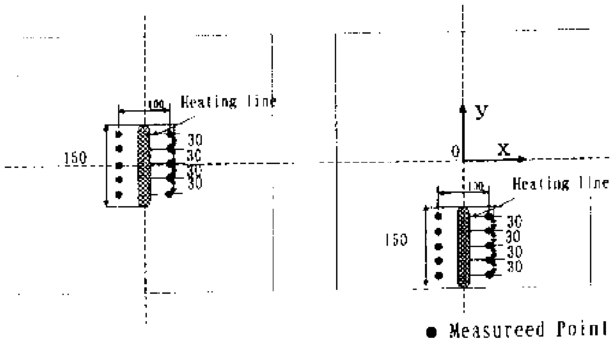
Then, another set of inherent strain corresponding to the size of primary heating is given to the simulated secondary heating. The result, as shown in Table 2., illustrate an elongation deformation during the secondary heating, confirming the pertinence of the assumption.

Table 2. Deformation obtained by parallel heating simulation (mm)

Element No.	Shrinkage (δ m)	Yang modullas
Heat 1	0.05801	21000
Heat 2	0.20656	1.0

(2) Effect of Heating on the Edge of a Steel Plate

There seems to be a definite trait that heating on the edge of a steel plate produces less deformation compared to heating given toward the center of the plate. This section discusses the experiment and thermoelastic-plastic analysis made to quantitatively determine the said effect. To the sample piece as shown in the Figure 3, a brief immobile heating is applied at the center of the piece and at an edge of the piece, thereafter deformation on the heated surface and opposite surface in traverse direction to the heating line was measured by a contact strain meter. Measured displacement at measurement points are plotted in Figure. 4.



(a) Heat at the center (b) Heat at the edge

Figure 3 Pieces for experiment

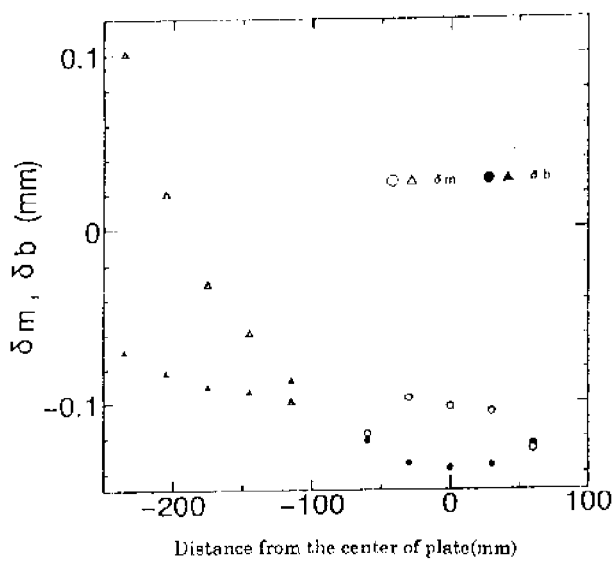


Figure 4 Measured displacement

In the figure, δ m represents the mean value of deformation on the heated and reverse side of the plate (in mm), indicating the contraction-elongation deformation of the neutral surface. δ b shows 1/2 of the difference between the deformation on the heated side and opposite side of the plate, representing the value of bending deformation toward the exterior of the surface. δ m which are marked by ○ and △ equal 0mm within 50mm from the edge, making the deformation on the edge an elongation. δ b which are marked by ● and▲ show, between the edge and the center, about 70% of the deformation at the center of the piece, indicating lesser deformation than δ m.

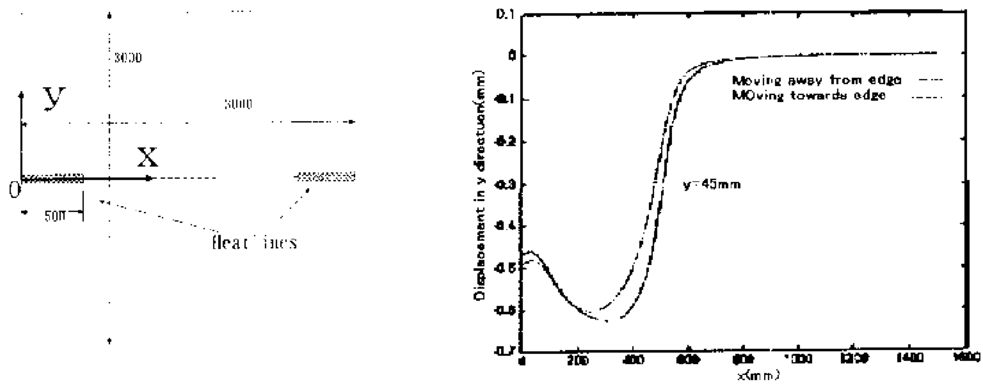


Figure 5 Thermoelastic-plastic simulation on the edge heating

Figure 5 represents the simulation result of two-dimensional thermoelastic-plastic change associated with inplane deformation upon heating on the edge of a plate. In the calculation model in Figure (a), an inplane contraction upon heating from the edge of a 3m x 3m x 16mm steel plate for the length of 500mm toward the center is shown. Results of calculation in case of heating from the edge of the plate to its center and from the center of the plate to the edge were compared without any significant difference. Deformation along the heating line near the edge of the plate is found to be approx. 60% of one near the center.

2.2 Development of the Curved Surface

An elasticity calculation allows free deformation in the direction of the inplane in order to compel conversion of the targeted curved surface into a flat surface. This is to simultaneously obtain the strain distribution that gives the targeted curved surface and the shape of the original flat surface to be worked. In other words, the obtained shape of the original surface perfectly match the targeted curved surface in terms of a mapping via a set of inherent strain. The set represents the strain distribution to be applied to the original flat surface to obtain the targeted curved surface, therefore is named required inherent strain. It becomes the ideal targeted set of inherent strain distribution to be resulted by the set of heating line arrangement to be subsequently determined.

The output of the inherent strain distribution correspond to the required amount of heating for the intended bend process, and to some extent to the degree of difficulty of the bend process. Also, this development method is applicable to variety of shapes.

An FEM calculation of compulsory transformation has been run for the outer bottom shell of the bow of a small freighter. Configuration of the object shell is shown in Figure 6.

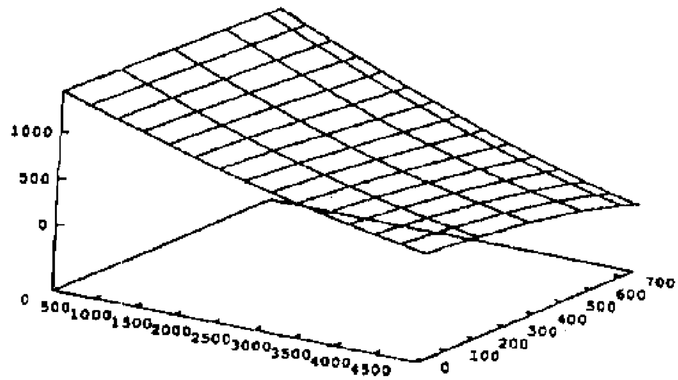


Figure 6 Configuration of the outer bottom shell of a small freighter

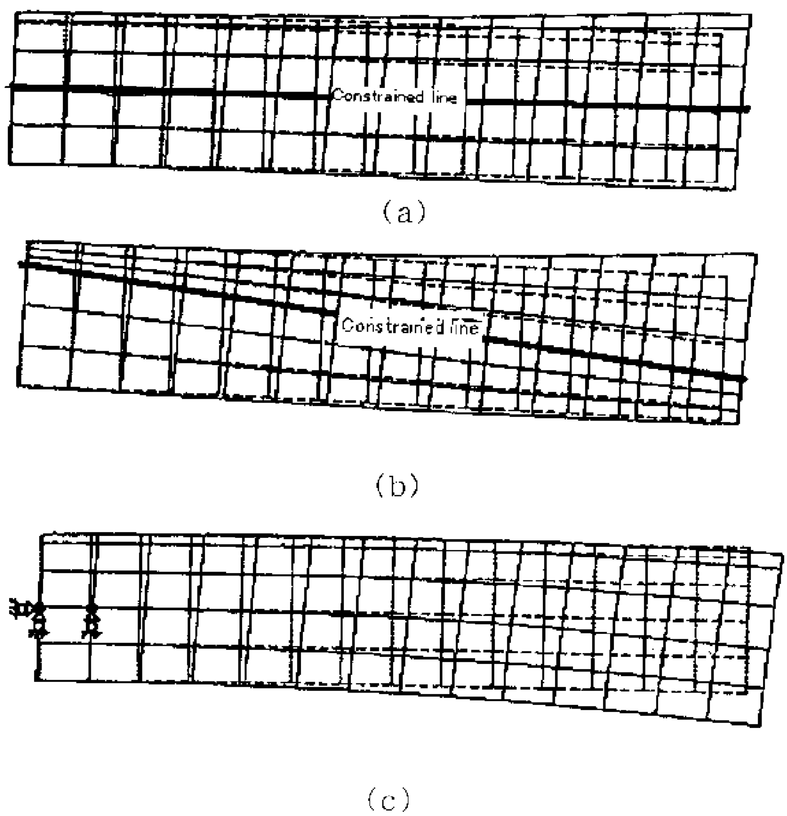


Figure 7 Development under different restrain condition

To develop required shape, three different condition of constraint were selected as seen in Figure 7 (a), (b), and (c). In (a), the constraint was imposed longitudinally along the center line of the object. In (b), the constraint was imposed along the diagonal axis of the torsion. (c) is where attempt is made to minimize constraints so that deformation will be as free as practicable, by constraining only two points near the lengthwise edges of the plate. The three developed shapes show noticeable difference.

Figure 8 shows the aggregate of absolute value of strain over the entire surface of the steel plates among the said three different developments. (a), (b), and (c) in the figure correspond to development (a), (b), and (c) in Figure 7.

Two bar graphs represent inplane contraction strain and the bend strain and their added values respectively. They serve as the quantitative appraisal of the three methods in a sense that the smaller the added value of strain over the entire plate the easier the work in bend processing, to identify a better method of development.

Most of the difference between the three are the difference in the quantity of inplane strain, which in turn is generally related to the required extent of contraction strain, as one might guess, dictating facility or difficulty of the bend processing.

Of the three, development (c) shows the least value, while development (a) and (b) shows little significant difference. The index also may be used as a convenient evaluating tool in selecting the position of joints to separate the curved surface.

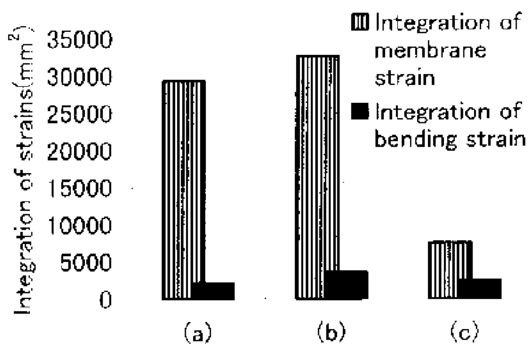


Figure 8 Comparison of the aggregate of absolute inherent strain in each development

2.3 Development of Simulation Methodology

In order to ascertain what deformation is generated by a inherent strain (produced inherent strain) caused by a certain heating line, a computer program which estimates a surface configuration as the result of elasticity calculation by entering discontinuous inherent strain of heating lines into FEM grid as equivalent nodal point force has been developed. The program is an indispensable subsystem in assessing the relevance of calculated heating line arrangement as discussed in the following section. Further, since the system can display the effect of manually selected heating line arrangement on the screen, it may be useful as a training simulator for linear heating specialists.

2.4 Calculation for Heating Line Arrangement

When line heating is manually designed, determination of the heating line arrangement to obtain a desired curved surface is an art that requires the most experienced and skilled specialists. It is the core technique in the present automation. Any strain comprise of mutually independent inplane element and bend element. Also, inherent strain created by a heating line has its own longitudinal and transversal components. With using these heating lines possessing such characteristics, a heating line arrangement which can create as a required inherent strain as close as possible must be derived.

Heating by immobile heat source for a fixed period of time had been studied as an alternative in the earlier stage of the research. (2) The method was ruled out against the quicker and more effective continuous heating by means of mobile heat source as the method to be implemented. Among the developed calculations, contour heating method to generate bend strain and method to place heating line athwart the direction of inplane strain component will be introduced in this section.

(1) Calculation of Continuous Heating Line to Create Bend Stress

The principle of the calculation we have adopted is based on inference from the contour lines of topographical map as illustrated in Figure 9. In the topographical map, elevation z is an integral of contour lines. When pitted against heating line arrangement requirement, it will be as in Table 3. To obtain requisite heating line according to the contour line, gradient surface distribution of targeted surface configuration which main bend strain is integrated needs to be obtained. The heating line is to be derived as a contour line with an even gradient on the gradient surface.

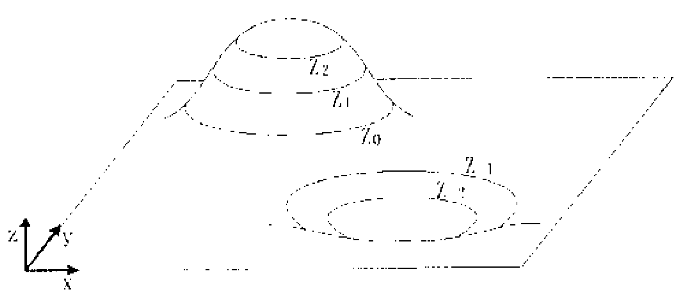


Figure 9 Topographical map and contour line

Table 3 Comparison between contour map and heat line arrangement

Contour map	Heat line arrangement
Altitude	Slop
Contour	Heat line

Distribution of the bend element of the required inherent strain is gradual as is exemplified by the cup shape surface of Figure 10 whose targeted inherent strain is in Figure 11, or the difference between the direction of heating lines that are selected by the developed method presented here and the direction of the main strain is small. Therefor the chances of creating shear elastic strain by the derived inherent strain of heating line are small, and an effective creation of deformation is possible. This method is then applied to a saddle shape curved surface shown in Figure 10.

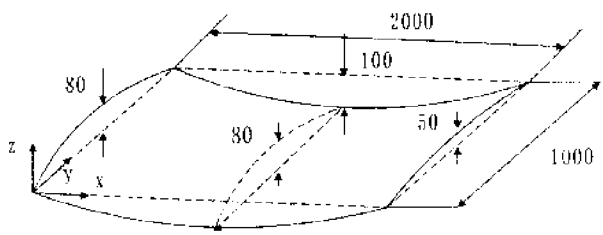
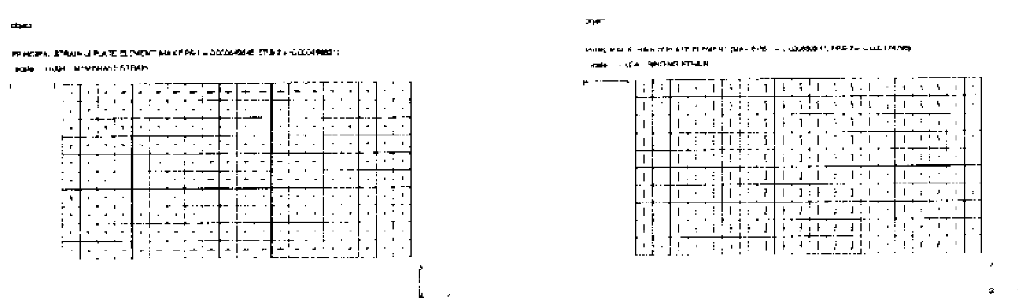


Figure 10 Shape of objective curvature



(a) Inplane strain (b) Bending strain
Figure 11 Distribution of required inherent strain

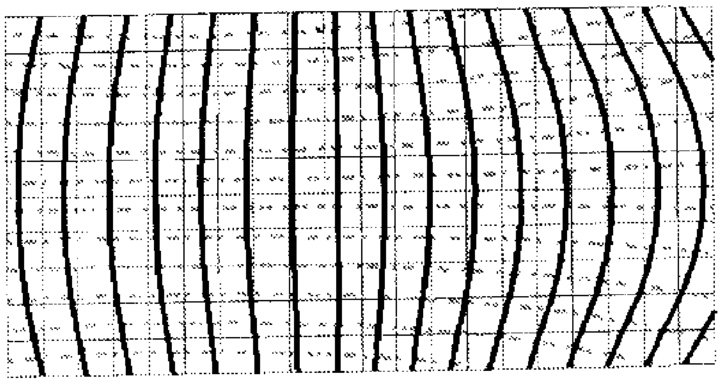


Figure 12 Obtained heat lines arrangement for bending

Herein heating condition at 37kW-2,336mm/min. and 935mm/min. rates is applied. Obtained heating line arrangement is shown in Figure 12. A pair of heating lines is obtained which diagonally across each other corresponding to slopes of two main axis. The broken line indicates bottom surface heating line and the solid line indicates upper surface heating line of the targeted surface configuration in Figure 10.

(2) Calculation of Heat Lines to Cause Inplane Strain.

Required inplane strain distribution to create a saddle shape curved surface is illustrated in Figure 11(a). As will be obvious, distribution of inplane strain is far more complex in direction and larger in variation in dimension. It makes the use of the equal contour line method as in the case of bend heating lines impracticable. On the other hand, patterns of inplane bend distribution to induce the same contorted topography are numerous. This may be easily surmised from the fact that various methods of projection are available to approximate spherical distribution of locations to prepare a world map.

Because single line heating is unable to produce shear strain, it must be combined with heating lines perpendicular to the direction of intended main strain in order to achieve the strain to produce desired surface configuration. To help achieve targeted condition, distributions of compressed two elements εx and εy which diagonally cross with and equal to the originally sought inplane strain distribution are repeatedly calculated. (2)

Calculated diagonally intersecting compressed strain distribution with respect to the saddle shape configuration of Figure 10 is shown in Figure 13. In comparison to Figure 11(a), direction of main strain is diagonally laying neatly in the direction of x and y. As against the above parallel inplane inherent strain, heating lines that will substitute its values are calculated.

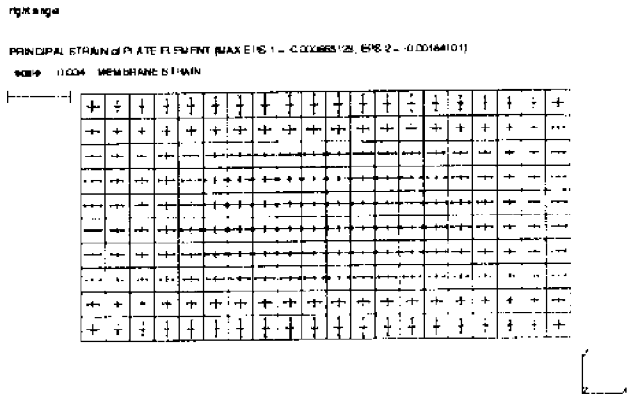


Figure 13 Distribution of orthogonal compressive inplane inherent strain

Heating conditions for the heating lines to be arranged are automatically maintained to have distance from each other to avoid interference from residual stress of adjacent heating.The sample calculation here took 37kW at a heating speed of 290mm/min. as its condition. Heating line thus obtained is as shown in Figure 14. Figure 15 illustrates a simulation configuration using the inherent strain by the selected heating arrangement.

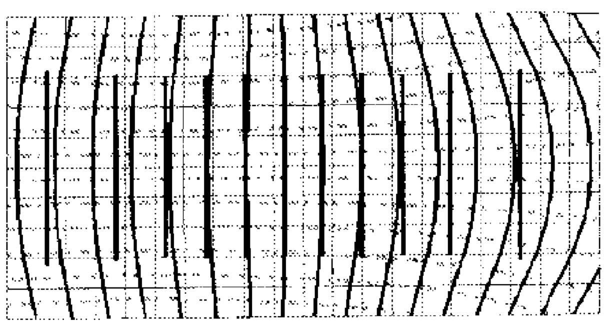


Figure 14 Heating lines for saddle shape

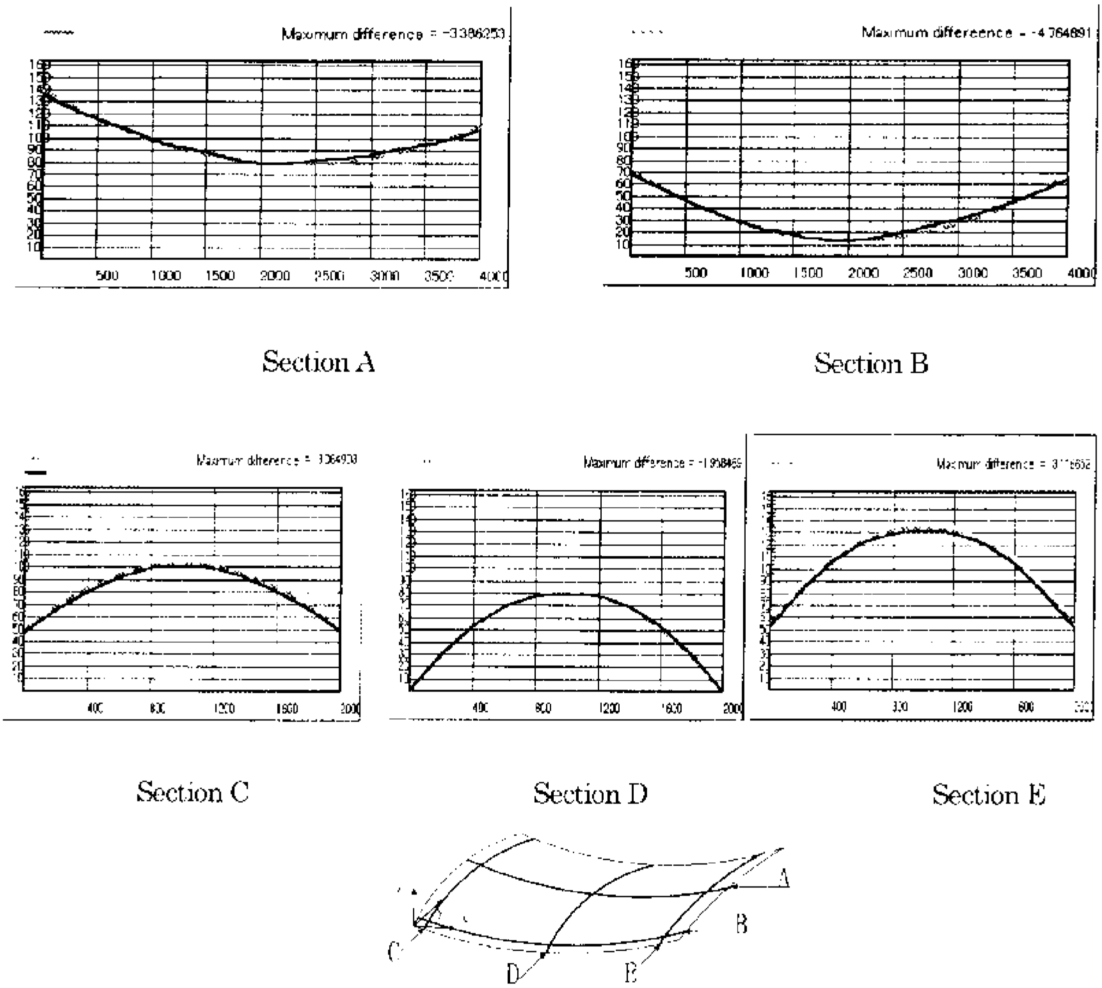


Figure 15 Objective and obtained shape by calculated procedure

3. Structure of Practical System.

A practical system which we have developed and introduced into the production line comprise of heating arrangement calculation system, heating device to apply the calculated arrangement to the object steel plate, evaluation system to measure the obtained configuration upon heating, and work table to support the steel plate to be processed.

3.1 Data Processing System.

Control data processing of the system structure other than arrangement selecting system, consists of the following sub-systems.

(1) Creation and reception system of the shape of vessels

A delivery program to generates position data on FEM grid from vessel data representing the curved surface of the outer shell, and then transfer them to the elastic analysis program.

(2) Conversion system for heating arrangement into NC device control data

The program translates the heating arrangement plan calculated via FEM simulation into a machine language that the NC device may understand, which in many aspect is analogous to other operating programs for NC cutter.

(3) Conversion system for measuring plan into NC device control data

The program translates the measurement points and the order and timing to perform such measurement into a valid machine language.

(4) Data transfer system

The program convey the heating arrangement plan to NC device via control PC, and measurement data of the obtained surface from the device to remote analysis computer.

3.2 Structure of the Devices

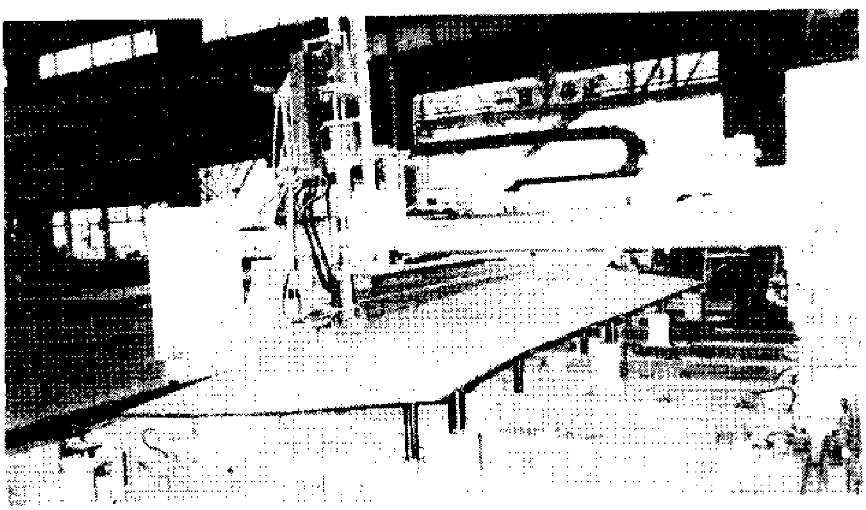


Figure 16 Apparatus for automatic line heating

The system comprises of hardware as shown in Figure 16, with capabilities that are hereinafter described.

(1) Heating Coils

Concentric coils of 80mm diameter is adopted. Its advantage is required less number of NC control axis due to non-directional nature of concentric coils. Heating experiments confirmed that it generates larger bend deformation when compared to the result from narrower hair-pin coils.

(2) Curved Surface Tracking Mechanism

To insure heating with precision, it is necessary to keep the distance from the surface of steel plate to the heating coil constant (at approx. 5mm) while it travels over the heating line. Vertical movement of coil is actuated by bearing motion pipes and revolving movement by universal joints.

(3) Measurement of Configuration and Evaluation Mechanism

Configuration of a steel plate is obtained by repeating laser measurement of elevation at a certain numerically determined x-y coordination point. Result of measurement is transferred to the control PC which will compare the received reading with the planned configuration for evaluation.

(4) Support of Curved Steel Plates

In order to support a steel plate that would be subjected to gradual deformation from flat to curved surface, multiple hydraulic jacks with long stroke are placed on the worktable. Height of jacks are automatically controlled to accommodate intermediate and final topography of the processed piece.

4. .Exemplary Processing of Curved Outer Shell of Vessel

Exemplary processing by the practical system described in Chapter 3 upon calculation of heating line arrangement corresponding to the inherent strain as discussed in Chapter 2 is explained in the following.

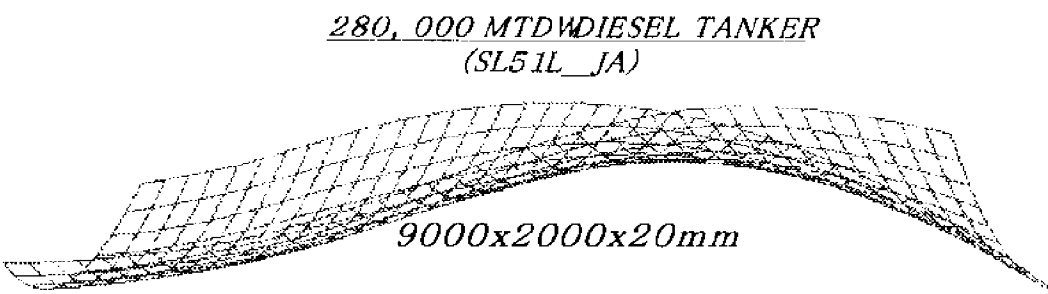


Figure 17 Target configuration of bow bottom shell in VLCC

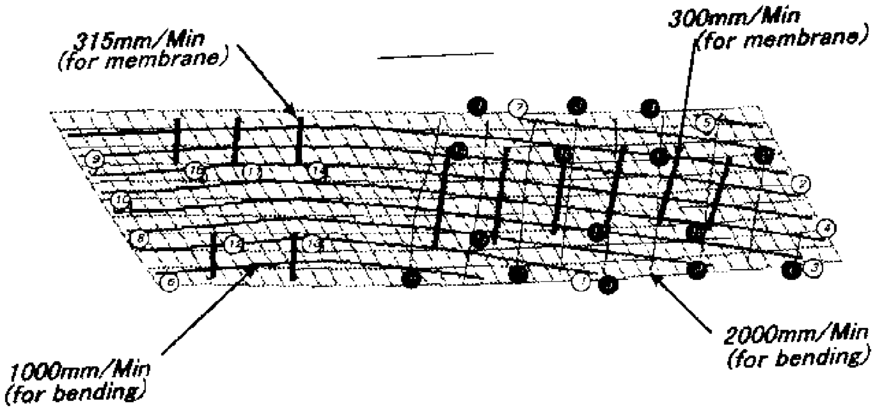


Figure 18 Calculated heating line arrangement

4.1 Result of Processing of the Object Component

Treatment of an outer shell near the bow of a VLCC is introduced here. The diagram illustrated in Figure 17 enlarge the z axis direction by 10 times, and shows an S shaped curved surface, half of which is saddle shape and the other half cup shape. To work out bends to produce such a configuration, both sides of the plate require heating.

Figure 18 (Calculated heating line arrangement) exhibit the arrangement of heating lines required for the purpose of such bend processing. Extent of heating by the heating line is controlled by the traveling speed of the heat source coil. Solid line of the graph shows the heating line on the regular surface, and the broken line shows heating line on the reverse surface of the plate when the plate is turned.

4.2 Processing Performance on Production Line

The system has been put to actual use to date for the outer shells of VLCC that are continuously constructed at Kure shipyard of IHI. Heat treatment speed increased to two to four times the conventional manual operation. Measuring time with 500 to 1000 measurement points on FEM grid averaging 40 minutes per plate may be further improved due to its highly repeatability. Another area that could be refined is the reversing of the work piece, which calls for upgrading of such peripheral equipment as the worktable and the handling crane for better efficiency.

5. Conclusion.

Linear heating that does not require large scale investment while allowing relatively liberal processing of curved surfaces for vessels is a technology that has been developed and became popular in Japan and elsewhere. However, limitation existed due to the fact that to design arrangement has been a difficult art which learning depended on individual ingenuity because for one thing the relationship between the heating and ensuing deformation is complex and for another process reproducibility has been unreliable.

We have developed a system to calculate the required heating arrangement to create the intended curved surface configuration with reasonable reliability after quantitatively clarifying the relationship between the heating and deformation. NC heating device has been constructed to implement the designed heating arrangement to actually produce outer shell profiles for vessels under construction. Test results sufficiently confirm the practicality and reliability of the quality of bend processing, to eliminate traditional limitation of the processing.

As its secondary effect, subsequent assembly work is expected to become much easier owing to improved accuracy of the bend processing.

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NC PAINTING ROBOT FOR SHIPBUILDING

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1. Introduction

So far, the automation of production in Japanese shipyards has been focused on the cutting & welding activities and it has greatly contributed to the improvement of productivity or quality. Especially the popularization of NC cutting machines has promoted not only "Hardware" effect(rationalization like unmanned operation of marking and cutting activities) but also "Software" effect(innovative advancement of supporting system technology to operate the machine effectively). Namely, it played a role of explosive energy to promote remarkable improvements of whole shipbuilding activities such as manufacturing method, production system and management. In particular, it is remarkable that the improvement of dimensional accuracy by NC cutting contributed to the improvement of manufacturing method at the subsequent progress of work.

By the way, Figure 1 shows the composition of number of workers by discipline in the shipyard. It shall be noted that the percentage of painters is equal to one of welders and the both activities are currently 23% of the total number respectively. Even if we automate only welding activity, the total cost saving effect is small in the whole shipbuilding activities. Japanese shipyards are now living in the times when the approach to automation for painting and fitting can not be bypassed because they also show the large percentage for the total man-hour. Especially the painting cost is rapidly increasing due to the shortage of painters. Furthermore, the paint area has remarkably increased due to the application of double hull structure to VLCC based on the IMO/MEPC requirement(1.5 times of single hull). Therefore, automation of painting activity is the most urgent development subject in the shipyard. Depending on these background, the authors have started the development of NC painting

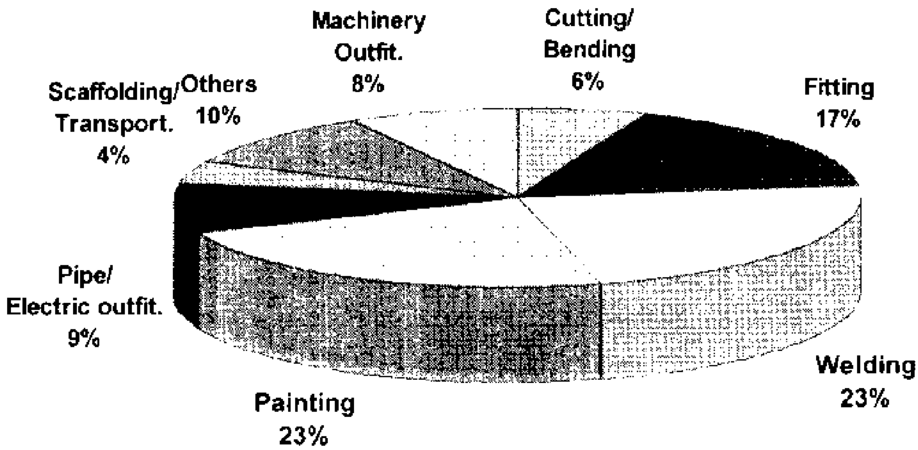

Figure 1 Composition of Number of Workers by Discipline

robot for shipbuilding since 1991 and recently succeeded in the development of a unique robot, which enables to realize automatic painting in the water ballast tank of closed double hull blocks. The developed robot has been applied for the production of VLCC. This paper reports the outline of developed robot and the application status for the production of double hull VLCC.

2. Development History

Figure 2 shows our development target on the application scope of painting robot for a double hull VLCC(307,000 DWT type). The area to be painted of a VLCC is total 390,000 m^2. About 60% of it has been painted on land(including painting shop) and the remained 40% has been painted in dock. Automation for the all is unrealistic in terms of economical and technical points of view. Based on a fundamental concept that just the bad working environment where human dislikes shall be automated, the authors tried an approach of automation for the painting activity inside water ballast tank(WBT) of double hull structure.

The development of painting robot for shipbuilding is regarded as a highly developed production technology which requires a concentration of potentials of global technologies such as CAD/CAM, robots, IT and ship-design/building, etc. and there are no president in the history of shipbuilding worldwide. Metaphorically speaking to the development of submarine oil field, the authors are in the stage that we have just started the real mining of crude oil finding a hopeful oil field at last after repeating trial digging for a long period.

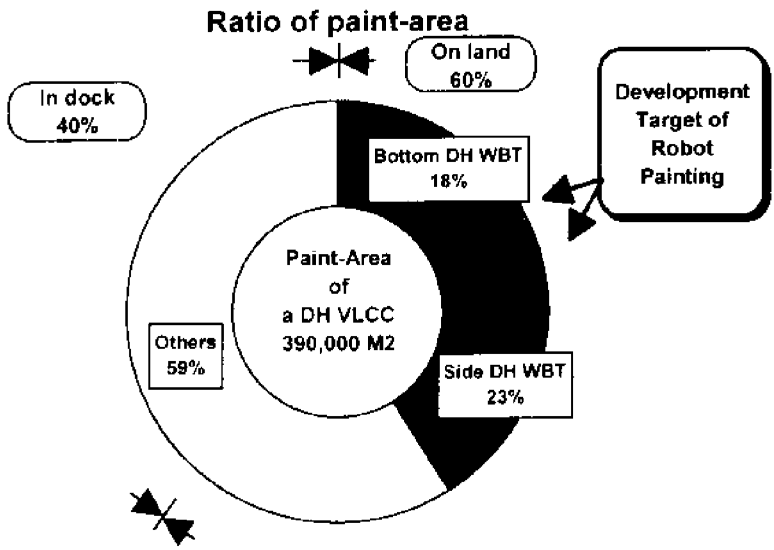

Figure 2 Application Scope of Painting Robot for a Double Hull VLCC

The development has been promoted dividing into two steps. The 1st step development is based on an application concept of painting robot for the opened double hull unit block with the dimensions of max. 25m length and max. 14m width. After turning over of a block, the robot approaches upward to the block as shown in Figure 3. The painting robot system consists of a CAM system linked with 3D CAD system, a controller, an automatic painting machine, and a robot main body. The robot main body consists of a unique placer with 3 axes freedom utilizing a λ type link-mechanism and a compact manipulator with 6 axes freedom. A prototype robot was developed and the feasibility study of robot painting for shipbuilding was carried out [1]. But through the 1st step study, the authors got a conclusion, namely it is difficult for us to find economical merit in case of the application for the opened double hull unit block because the applicable area of robot painting is obliged to be limited in order to avoid the damage by welding of subsequent stage.

So, changing the application concept of robot, the authors have started the 2nd step development since 1996. The 2nd step development is a challenge of real automation for the closed double hull block, whose grand assembly and outfitting activities have been completed. According to this concept, as a matter of course, the block to be painted is the structure consisting of some divisions closed up from all directions and also all outfitting parts have been already fitted to the block. Compared with the application concept of 1st step, the technical difficulty increased remarkably. For instance, how shall we bring in the robot for the closed huge block ? How shall we let the robot move autonomously in the block ? And, how shall we avoid the interference between the robot and structural members including outfitting parts ?, and so on. Although there were so many subjects to be broken through, a confidence with tenacity might have led us to a success of development. (namely, we will be sure to succeed in the development provided that we could concentrate our global technical potentials cultivated until now.)

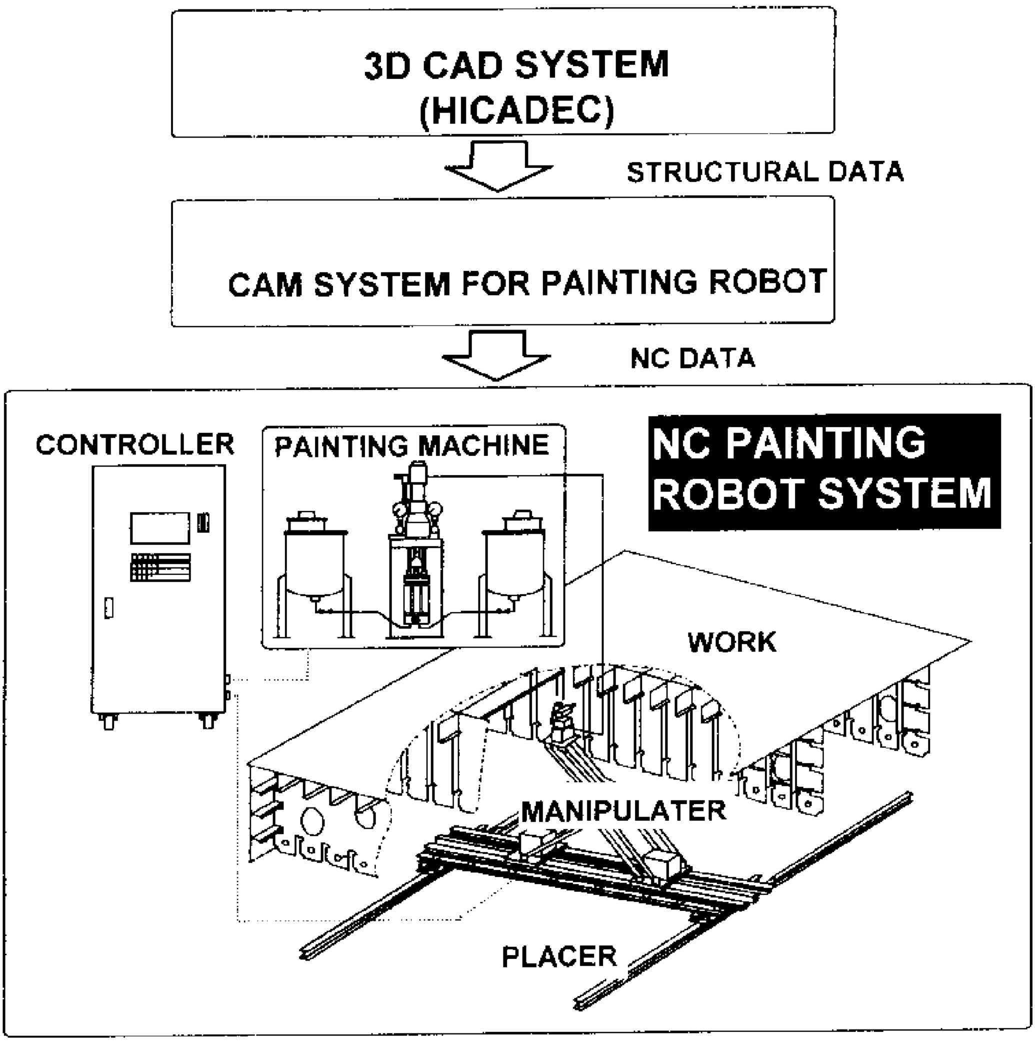

Figure 3 Application Style of Painting Robot for Opened Double Hull Unit Block

3. Painting Robot for Closed Double Hull Block

3.1 Application Concept

In case of the authors' shipyard, the double hull block of VLCC is gland assembled as a huge cubic block with 20m length, 30m width, 8m height, and the weight is approx. 650tons. In order to automate the painting activity of closed tank of such huge block, the authors devised a unique application concept of painting robot with following features: ① Use of self-driving type portable NC robots which enable to run on the face plate of longitudinal frames without rail. ② Each floor shall have a permanent opening (with the dimensions of approx. 800mm x 1.600mm) for passing through of robot in the structural design. ③ High adaptability for current ship production system since plural robots are optionally applicable to the block anywhere. ④ Investment scale of facility is very small, and nearly 100% robot painting is geometrically possible for the inside tank of closed double hull block. ⑤ Operation linkage between CAD/CAM and robot systems is possible in the shipyard CIM environment.

Figure 4 shows the schematic explanation of necessary consideration on the structural design of ship. Using the structural analysis program of classification society, the optimum location of permanent opening for the floor and/or the suitable stiffening method are discussed and reflected into the structural design of ship.

Figure 5 shows the transportation method of painting robots. The robot painting is carried out shifting a trailer mounted two sets of painting robot system from stage to stage. Two robots are operated by single operator.

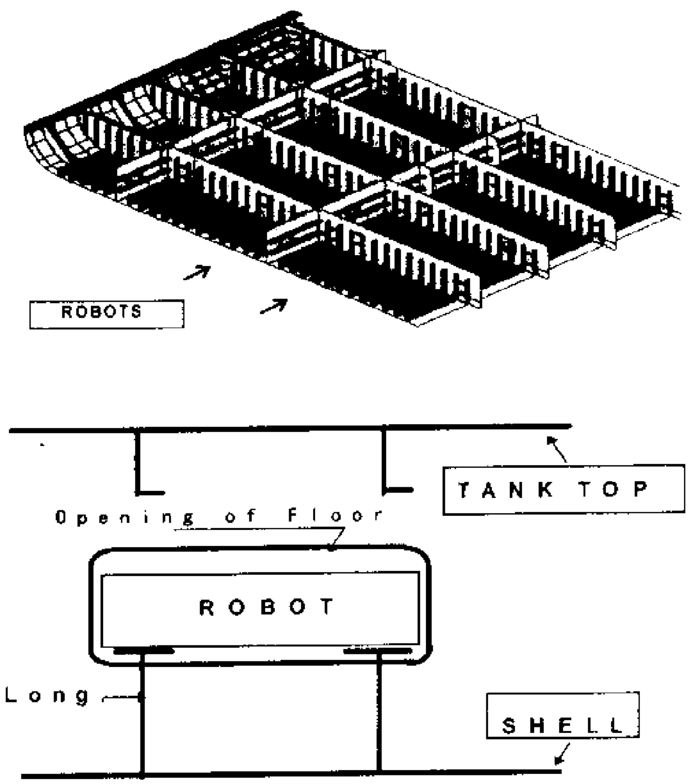

Figure 4 Necessary Consideration on Structural Design

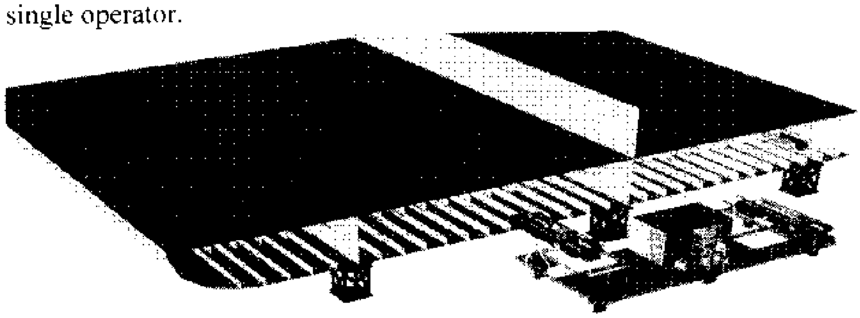

Figure 5 Transportation Method of Painting Robots

3.2 Hardware

3.2.1 Robot Main Body

The robot main body consists of a self-driving carriage, an external axes placer and a manipulator. When the robot enters into the block or passes through the opening of floor, the placer and the manipulator keep the most shrunk posture on the carriage as shown in Figure 6. The movement of robot main body and the automatic painting machine are perfectly controlled by NC data. The robot main body moves from the most inner division toward this side sequentially painting each division. Figure 7 shows the image of robot painting in the double hull tank.

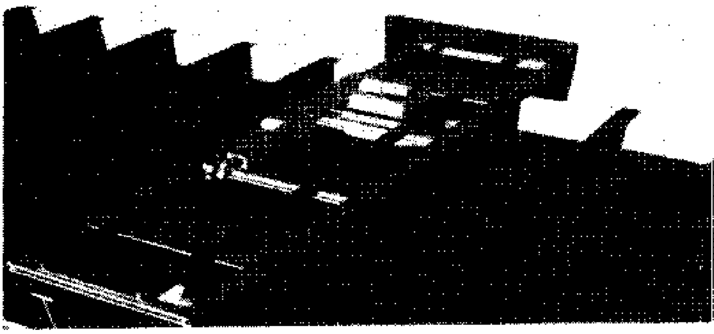

Figure 6 Robot passing through the Opening of Floor

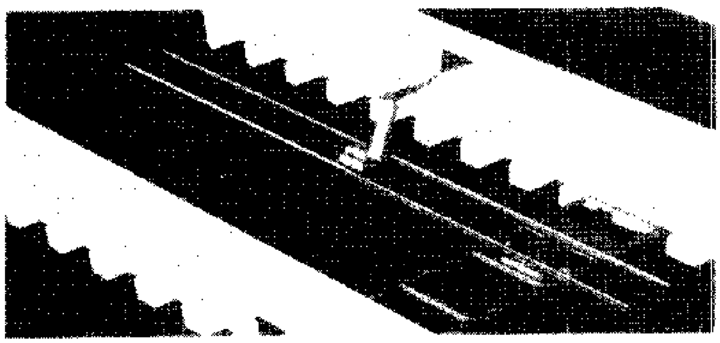

Figure 7 Image of Robot Painting in the Double Hull Tank

Manipulator: Articulated type manipulator with six axes freedom is very compact and light weight design. In case of the most shrunk posture, the manipulator can keep 300mm in height. On the other hand, it has sufficient movement range for the painting of double hull tank with about 3m in depth. Since the manipulator has been designed as a unique shape with long arm, the arm of cylindrical shape has been used in order to keep the necessary stiffness. "In-line type" manipulator as shown in Figure 8 is also one of highlighted features Namely, the paint is supplied through inside manipulator in order to avoid the damage of painted surface due to the handling of hose. It is a mandatory function for the painting robot for shipbuilding to be operated in the very narrow space. Regarding the countermeasure for explosion, internal air pressure type has been used.

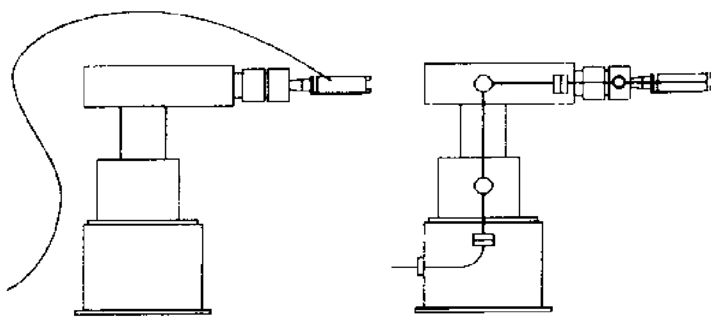

Figure 8 In-line Type Manipulator

Placer: The role of placer is to move an origin of manipulator to the suitable location in a division surrounded by floors and girders. It is the external control axes of two steps telescope mechanism with five axes freedom as shown in Figure 9.

Self-driving carriage: The self-driving carriage mounts the above mentioned placer and manipulator, and it runs on the faces of two longitudinal frames without rails by utilizing two sets of magnetic crawlers.

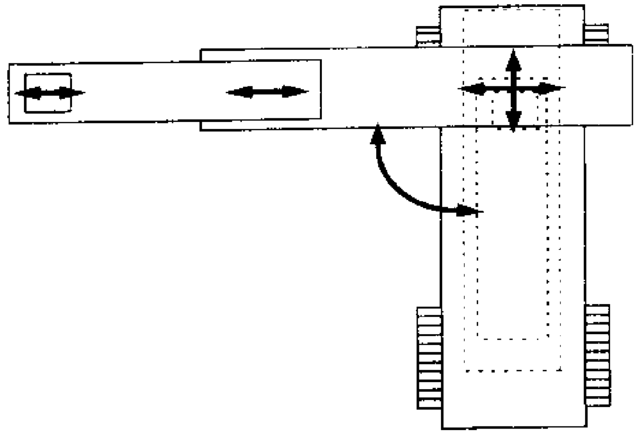

Figure 9 Freedom of Placer

3.2.2 Controller

A PC-based controller has been developed, whose CPU is Intel Pentium 150MHz, OS is Windows NT, and it uses an object oriented control method considering the performances of high speed processing and possibility of extension.

3.2.3 Automatic Painting Machine

Two liquids mixture type paint(Tar-Epoxy) is used for the water ballast tank of double hull. The base material and the hardener are homogeneously mixed by the automatic painting machine and airless sprayed. The start/end of painting are controlled by NC data depending on the instruction from the controller.

3.3 Software

The CAM system for painting robot (so called CAMEX-Paint) automatically generates the movement data of robot based on the structural data output from the CAD system (HICADEC-H) [2] and the outfitting data output from the product model (PHI) [3] or by manual input as shown in Figure 10. And it outputs the NC data, the application plan and the management data. The specifications of painting and

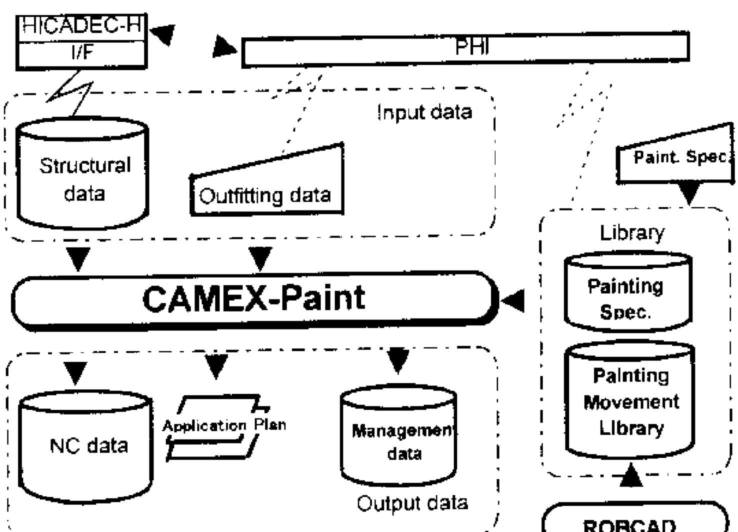

Figure 10 CAM System for Painting Robot

the painting library has been preliminary prepared and they are referred in the process of CAM system and incorporated in the NC data. Furthermore, a simulation system of painting robot utilizing the ROBCAD has been also developed in order to support the operation. It has been used for the purposes of the interference check between robot and work and the preliminary simulation of coating thickness of paint.

3.3.1 CAMEX-Paint

The CAM system for painting robot has been developed in the environment of Pentium PC, Windows-95, and Borland C++ Builder using the software technologies which the authors' have cultivated in the field of welding robot up to now. Namely, an object library so called CCL(CAMEX Common Library) was utilized considering the efficiency of development and the performance of maintenance, which the authors' had been already developed for the CAM system of welding robots [4]. Figure 11 shows the CCL data structure for painting robot. The part of "Structure" is just the same to one of welding robot and the parts of "Recognized structure" and "Movement" were newly extended for the painting robot.

Input data: Input data consists of structural data and outfitting data. The structural data has been expressed by IGES format composed by geometric data of structural parts and the attributes such as ship no., block name, and parts name, all of which are sent via an interface(I/F) [5] from HICADEC-H. On the other hand, the authors are currently difficult to get the correct shape of the outfitting inside double hull tank such as ballast pipes, anodes, steps, and grips, etc. since the full application of outfitting CAD system and product model have not been realized yet. Therefore, the outfitting data has been used for only the purpose of interference check by inputting the locations and the outline dimensions of them. They have not been painted by the robot.

Output data: Output data consists of movement data, application plan, and management data. The movement data of robot and the pattern data of painting are output to the file. All movements of the self-driving carriage, the placer, the manipulator, the start/end of painting are controlled by the NC data. The application plan includes following items: ① Name of NC data, PROG No., & JOB No., ② Structural information of work(ship No., block name, wing or center tank), ③ Drawing of painting area, ④ Drawing of area to be reserved painting. The management data includes following items:

a) Area subject to painting(m^2) : Total area to be painted.
b) Actual painted area(m^2) : Total area of actual painted element surfaces.
c) Reserved area of painting(m^2) : a - b
d) Ratio of reserved area(%) : c / a * 100
e) Painting time(min.) : Distance of painting * Velocity
f) Air cut time(min.) : Distance of air cut * Velocity
g) Operation time(min.) : e + f
h) Consumed paint(l) : e * spraying velocity

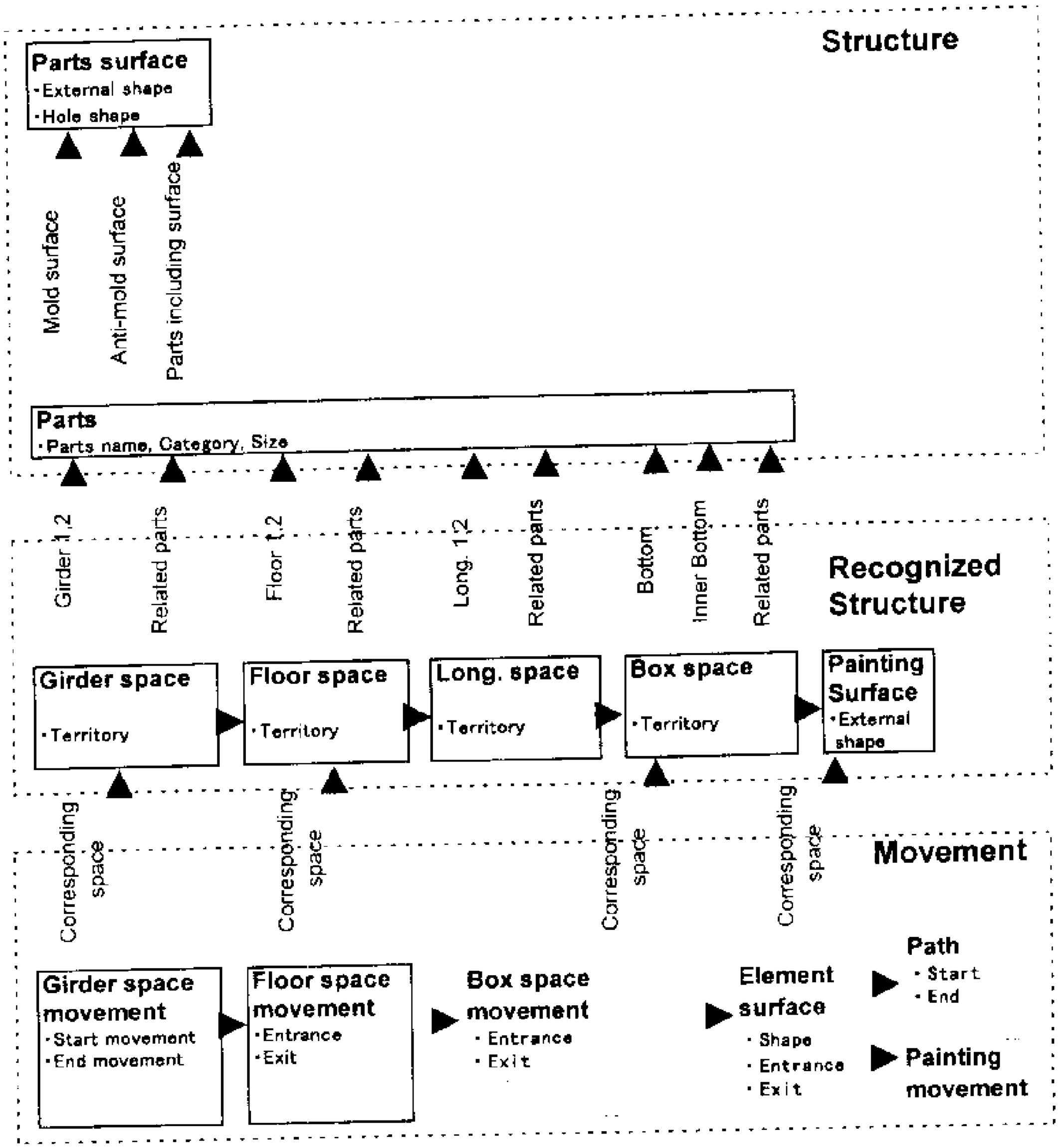

Figure 11 CCL Data Structure for Painting Robot

Library: The library consists of painting specifications and painting movement library. The painting specifications are the necessary information of spray painting to be selected for each block. Following items are included: ① Name of painting condition, ② Coating thickness, ③ Number of layer, ④ Name of paint, ⑤ Coating thickness of dried condition, ⑥ Secondary pressure, ⑦ Chip No., ⑧ Spray distance, ⑨ Pattern width, ⑩ Painting velocity, ⑪ Accelerated velocity of painting start, ⑫ Accelerated velocity of painting end. The painting movement library is the necessary information of spraying technique for the robot, and it has been preliminary set to be able to automatically pick up.

Generation process of robot movement data:

The hull structure sent from HICADEC-H is recognized dividing into the girder space, the floor space, the long. space, and the box space. For the each space, the robot movement data is generated. The girder space is a division divided by two girders as shown in Figure 12. In case that a water tight bulkhead (W.T.B) exists in a block, the girder space is further divided by it. One girder space corresponds to PROG of NC data and it is a unit of continuous movement for painting robot. The floor space is a division divided by the floor within the girder space. The robot performs painting sequentially from the most inner floor space toward this side. The box space is a division which enables to paint by the movement of only the manipulator or the placer. Figure 13 shows the typical patterns of box space. For the each pattern, the robot movement pattern has been preliminary prepared, and actual movement data is automatically generated depending on the dimensions of composed members.

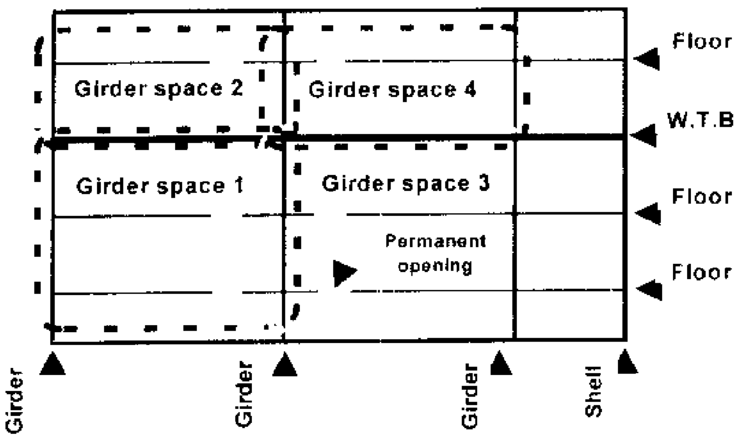

Figure12 Girder Space

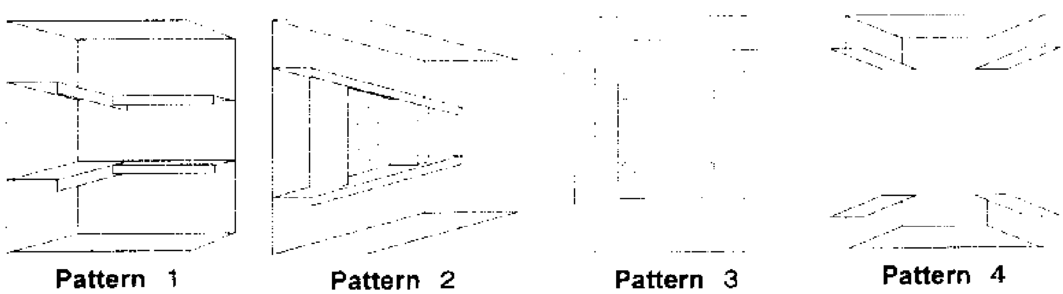

Figure 13 Patterns for Box Space

3.3.2 Painting Robot Simulation System

Utilizing a software on the market so called ROBCAD, the authors have developed a simulation system for painting robot in order to support the operation. The development has been carried out in the environment of Silicon Graphics Indigo2 R4400 Solid impact/IRIX V5.3, ROBCAD V3.5/DCM/

Paint-Master, G[1]. Figure 14 shows the outline of simulation system. It has been effectively utilized adding the following functions to the ROBCAD system: ① Interface to generate hull surface model automatically from HICADEC-IGES data(CAD I/F), ② Interface to supply the NC data output from CAMEX-Paint to the robot model within ROBCAD(Upload I/F), ③ Interface to perform the simulation based on movement mode(Simulation I/F), ④ Interface to output the NC data of amended movement(Download I/F). Figure 15 shows an example of simulation screen of robot painting. It is a very useful supporting system for the operation of robot, since it is effective not only for the discussion of optimum robot movement but also for the avoidance of trouble due to visual interference check and/or for the simulation of coating thickness of paint.

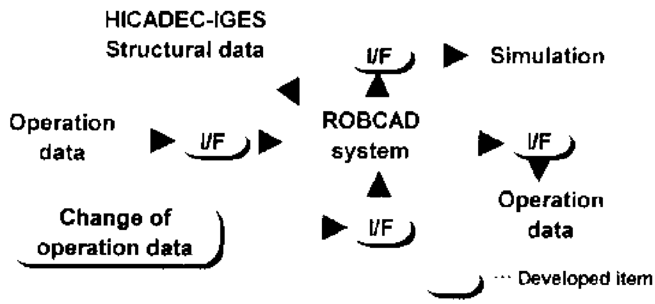

Figure 14 Simulation System for Painting Robot

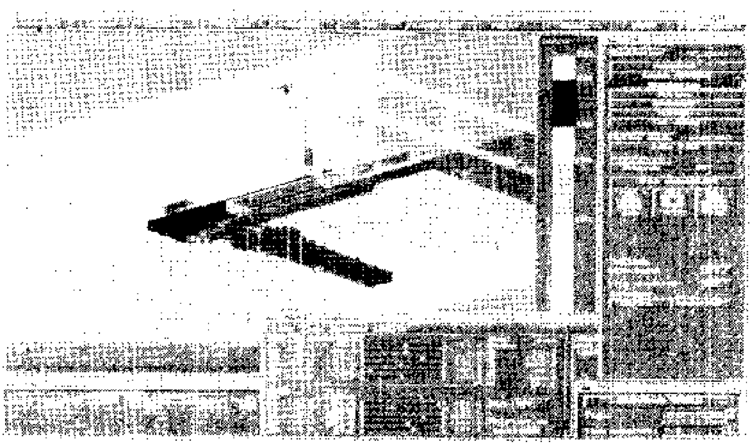

Figure 15 Simulation Screen of Robot Painting

4. Application to VLCC

The application of developed robot was tried for the building of 307,000 DWT type VLCC in June 1998 in the authors' shipyard. The applied block is the wing tanks of double bottom. Figure 16 shows the plan of applied structure, the possible area of robot painting, the impossible area due to geometric reason, and the actual applied area of robot painting. Table 1 shows the painting condition. The painting robot was applied in combination with a manual airless spray machine in lieu of automatic painting machine due to the unexpected trouble in this trial.

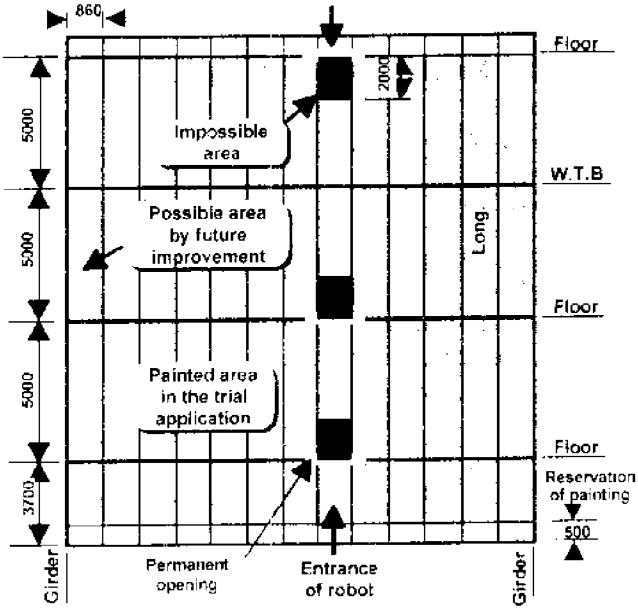

Figure16 Applied Structure of Painting Robot

Table.1 Painting Condition

Place	In painting shop
Atomospheric temp.	29 degree C
Moisture	70%
Painting machine	Airless spray machine
Brand of paint	Eposeal No.6000PS black
Coating thickness	250 micron (dry)
Heating	None
Mixing ratio of sinner	3%
Temp. of paint	28 degree C
Viscosity of paint	18 ps
Chip	623
Filter	60 mesh
Spray pressure	1st: 2.5 kgf/cm2
	2nd: 150 kgf/cm2
Velocity of painting	180 mm/sec.
Spray distance	400 mm

Figure 17 shows the painting robot entering into the block, Figure 18 shows the robot passing through the permanent opening of floor, and Figure 19 shows the status of robot painting in the closed double hull tank. Through the application to actual ship, it was confirmed that the painting robot has the sufficient durability and reliability for the continuous operation of long time. Human painter makes a effort to keep the homogeneous coating thickness by crosswise lap painting technique, and he carries out painting in accordance with a sequence: at first for the ceiling(overhead posture), secondary for the wall(vertical posture), and finally for the floor(flat posture) after cleaning the dropped dust on it. On the other hand, in case of robot, the specified coating thickness is available by single layer painting technique lapping the pattern width. Therefore, the robot painting enables a continuous painting with the sequence from the floor to the ceiling via the wall. Because the dust made during painting of the wall and the ceiling adheres on the correctly

Figure 17 Approach of Robot to Block

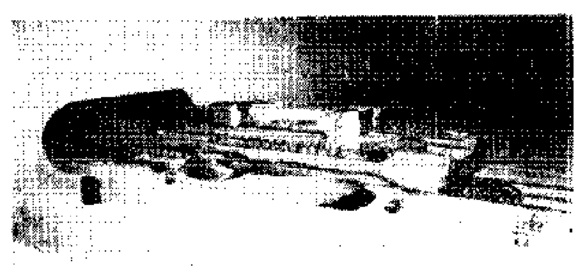

Figure 18 Robot passing through the Floor

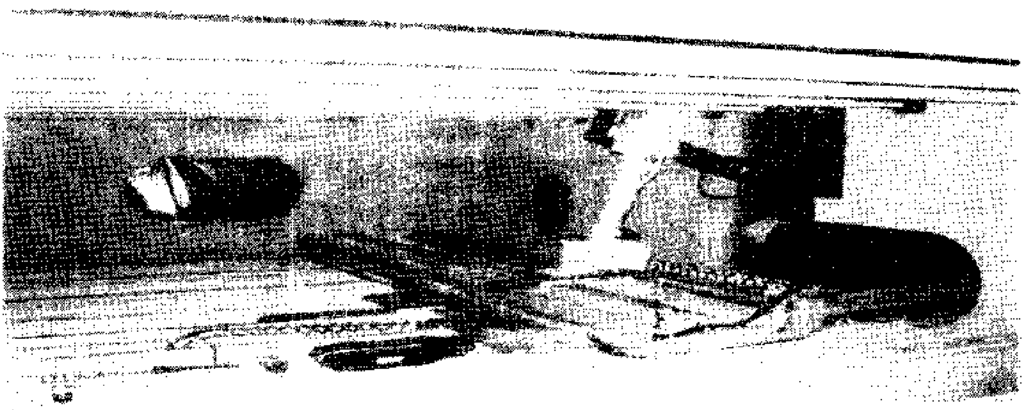

Figure 19 Robot Painting in the Closed Double Hull Tank

coated surface and it does not give any bad effect for the quality of painting.

Table 2 shows the actual data and future possibility of robot painting. Division by division, robot painting was carried out trying the improvement of software such as reduction of air cut time. Although the robot painting was applied for 75% of subject painting area in the trial application, the authors had a confidence that about 99% of subject painting area could be automated by the future improvement of application software. And the authors also has a confidence that the standard time of robot painting could be improved further 30～40% from one of trial application(0.027H/m^2) by the improvement of software. By the way, as a matter of course, the touch up for robot painting is necessary for the corner edges of drain hole or scallop like the case of human painting. Therefore, it will be the reasonable understanding that the efficiency of a robot corresponds to one of a skilled painter. The cost saving effect will depend upon the applying method of plural robots for a block. According to the authors' idea, 4 robots for a block could be simultaneously operated by 2 operators. Regarding the quality of robot painting, the specified coating thickness without any harmful defects was given for the all painting postures. And the consumed quantity of paint was same to one of human painting. Based on the successful application to actual ship, the authors' shipyard intends to positively promote the real automation of painting activity in shipbuilding.

Table 2. Actual Data and Future Possibility of Robot

Division	Subject painting area (m2)	Actual result of robot application				Future possibility of robot application		
		painting area (m2)	Consumption of paint(Kg)	Painting time(H)	Standard time(H/m2)	painting area (m2)	Consumption of paint(Kg)	Painting time(H)
No.1	390.7	335.6	240	9.93	0.030	385.9	280	6.95
No.2	419.9	305.6	220	7.65	0.025	415.1	300	7.47
No.3	388.1	332.9	260	8.62	0.026	383.3	300	6.90
No.4	244.4	101.7	100	2.57	0.025	244.4	240	4.40
Total	1443.1	1075.8	820	28.77	0.027	1428.7	1120	25.72
Ratio of area		75%				99%		

5. Concluding Remarks

This paper reported about the development of NC painting robot for shipbuilding which enables automatic painting of closed double hull block. Application technology of welding robot in shipbuilding has already advanced to the level that we can forecast the "Ultimate Automation" [1] during 18 years since the start of development. On the other hand, automation of painting is still a future subject. But, according to the challenge of Hitachi Zosen Ariake Works, the real automation of painting is also close to reality.

Automation of painting is a hopeful technology in terms of cost saving in shipbuilding. But, seeing the robot working silently in the closed narrow space, it is a honest impression of the authors that "a pleasure of releasing human from the bad working environment" was by far greater rather than arguing of economical effect.

Painting robot technology is expanding in its importance as a part of new generation shipbuilding research, and it will be essential for modernization of shipyards which utilize to a maximum extent of highly sophisticated production system.

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MULTI-ROBOT WELDING SYSTEM FOR CURVED SHELL BLOCKS

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Abstract

Inefficiency of curved shell block assembly has been remained a long years after various approaches for automation. For the solution of this subject, advanced multi-robot welding system has been developed in 1998. Developed welding system consists of CAD/CAM system, multi-robot control system, adaptive welding control system and gantry type multi-robot mechanism. Almost all the information for the robots are defined or autonomously generated with 3D CAD system originally developed in NKK. The robot motion data are generated in automatic robot programming system linked with CAD. Four sets of articulated welding robots hung on a mobile gantry access to the block and carry out the welding procedure by using generated robot program delivered from CAD/CAM system. Adaptive welding control system stores series of welding conditions associated with joint slopes and root gaps. The system detects the root gaps in real time with High Speed Rotating Arc sensor, then selects the optimum welding conditions. The welding system has been under practical implementation.

Introduction

In shipbuilding, automatic welding system has already been in practical use at the sub-assembling stage and at the parallel block assembling stage. In NKK, 10 robots with CAD/CAM system for subassembly[1], and 16 robots with OLP(Off Line Programming) system for parallel block assembly have been installed in 1995. However, the difficulty has been pointed out for curved block assembling. The block geometry has 3 dimensional curved shell and large and complex structure. Expertized welding procedure is required for unexpected root gap change with the gradually changed slope joint. Key technologies, i.e. CAD/CAM system, gantry type multi-robot mechanism and its control system, adaptive welding parameter control system and welding database, have achieved automation of mentioned works. The report describes the development of technologies for welding automation of 3 dimensional curved block assembly in shipbuilding.

Welding System

The configuration of multi-robot welding system is shown in Figure 1. The system consists of 3D CAD, robot simulator based CAD/CAM, multi-robot control, adaptive welding control and gantry robot mechanism.

Specification of 3 Dimensional Curved Block

Curved shell blocks are arranged on the offset base in order to keep minimum slope. The maximum size of blocks is 22m length by 20m width, and 8.5m height. Maximum slope of the joints is

20 degree in longitudinal direction as same as transverse direction, which defined as block geometry data. The inclination of the trans. panel is less than 20 degree (less than 1710mm overhang). Table 1 and Figure 2 shows a guideline specification of curved block geometry for the development. Also, Figure 3 shows the objective welding joints location in lattice cell.

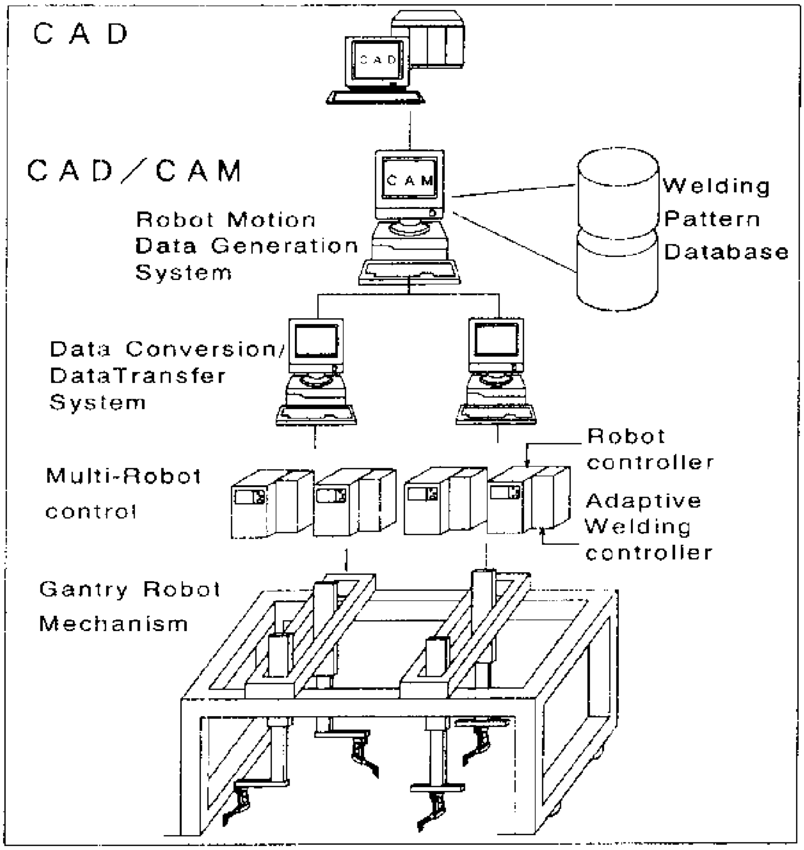

Figure 1 Configuration of multi-robot CAD/CAM welding system.

Table 1 Objective block specifications

Block Size	Length	22 m
	Width	20 m
	Height	8.5 m
	Trans. Space	3 m MIN
	Transf. overhang	1710 mm
	Longi. Spase	650 mm MIN (Face to face)
	longi. Height	800 mm MAX
Shell Slope	longi. Direction	20° MAX
	Trans. direction	20° MAX

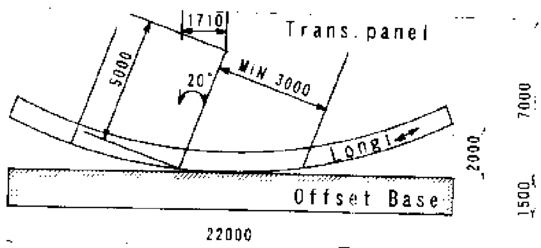

Figure 2 Objective block specifications

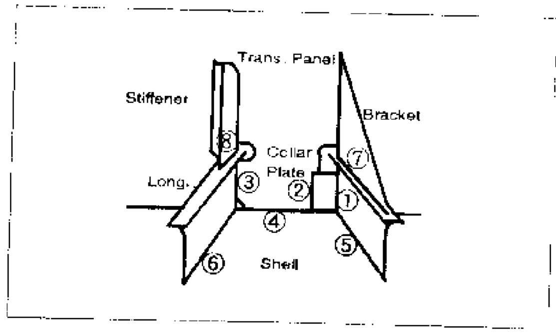

Figure 3 Objective welding joints in lattice cell.

Welding Process

GMA welding process is applied with flux-cored wire and 100% CO_2 shielding gas.

Slope Fillet Welding

High Speed Rotating Arc process (HSRA) is applied for slope fillet welding. Figure 4 shows the principle of HSRA process[2]. The arc rotation with mechanical torch motion provides more efficient and stable welding. Also, arc sensor system of HSRA provides various benefits for robot welding. Figure 5 shows the example of bead cross section in several slope conditions and root gaps. HSRA process achieves a good stability against root gap changing. The up-slope welding is applied for slope joint. Adaptive welding parameter control is applied for various slopes and root gaps.

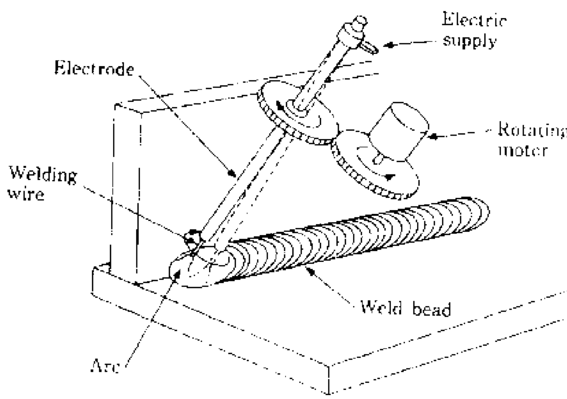

Figure 4 Principle of High Speed Rotating Arc welding process.

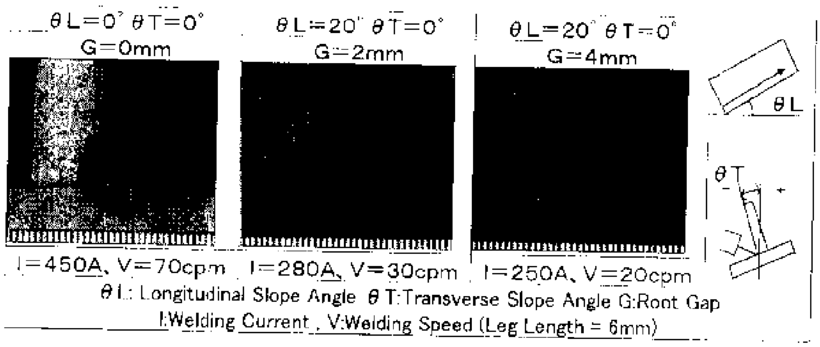

Figure 5 Bead cross section of slope fillet welding.

Vertical Fillet Welding

Conventional vertical up welding with weaving oscillation is applied in vertical fillet welding as the result of comparison with vertical down welding. Figure 6 shows examples of bead cross sections at several root gaps. An common welding condition is selected for inclination in vertical welding.

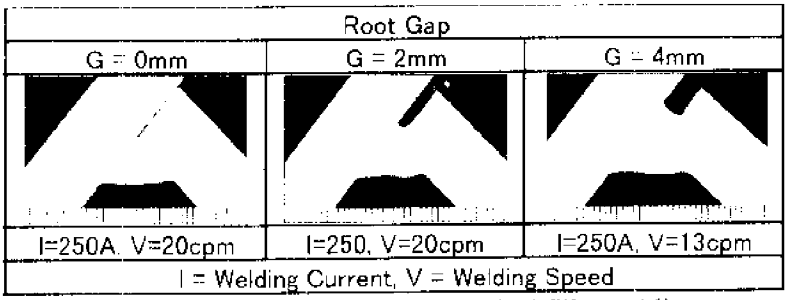

Figure 6 Bead cross section of vertical fillet welding.

Multi-robot System

Robot Mechanism

Four sets of multi-articulated type welding robot hung from mobile type gantry mechanism are installed. Figure 7 shows the configuration of multi-robot mechanism. 2 sets of transverse girder (Y axis) are arranged on the mobile gantry (G axis), 2 sets of carriage (X axis) are equipped on each girder, a vertical sliding column (Z axis) are mounted on the center of each carriage. Also, 2 sets of transverse sliding unit (L and J axes : Y direction) are hung from each sliding column as shown Figure 8. These sliding units assist the robot access to the overhung corner section. In addition, an revolving unit (P axis) is arranged under the sliding unit in order to cover the backside motion area of robot.

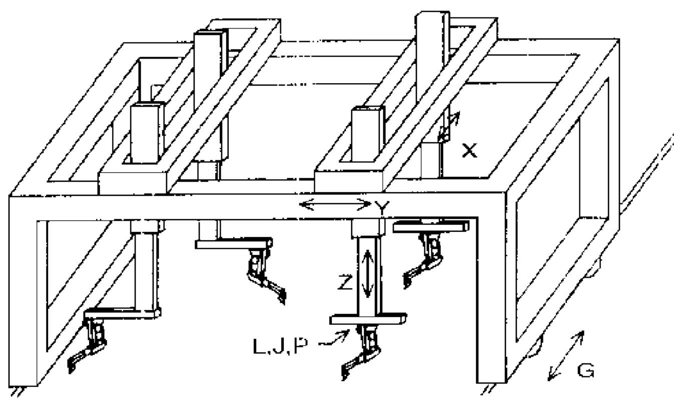

Figure 7 Configuration of multi-robot mechanism.

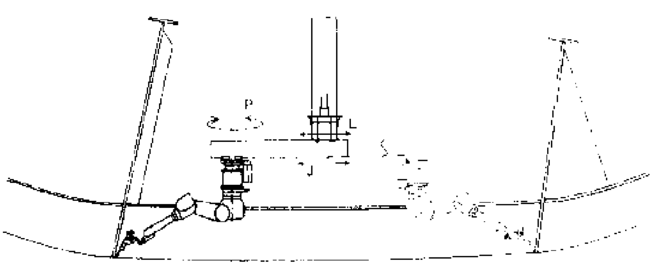

Figure 8 cooperative sliding unit and revolving unit mounted on the Z column.

Robot Control System

The robot control system consists of gantry control for positioning and articulated robot motion control for welding operation. The gantry controller operates G, Y, X, Z and P axes. Then, articulated robot controller operates 6 articulated axes and L, J, X axes as cooperative external axes. In particular, 2 sets of X axis driver are installed for each control. All of the gantry data and robot motion data are generated with a robot program in CAM system. The program is transferred into robot controller, after then, gantry data is transferred into gantry controller indirectly when the robot program is executed.

Robot Motion Flow

The robot motions consist of robot positioning and robot welding. An example of robot access motion flow into a block is shown in Figure 9. In robot positioning motions, firstly, mobile gantry (G axis) accesses to the block (workpiece). Secondly, transverse girder (Y axis) accesses to the side of the trans.-space (Unit) shared by the transverse panels faced each other. Thirdly, the carriage (X axis) accesses into the trnas.-space, then stops over the lattice cell between longitudinal stiffeners. Finally, vertical sliding column (Z axis) goes down upon the lattice cell as shown in Figure 10. After the robot positioning, robot welding motions are carried out, which are approach to the welding joint, wire touch sensing motion at start and end point, welding motion and retract from the welding joint. After the welding procedure at the front side of lattice cell is finished, the revolving unit (P axis) turns the robot by 180 degree to the back side. Above kind of welding sequence are carried out continuously.

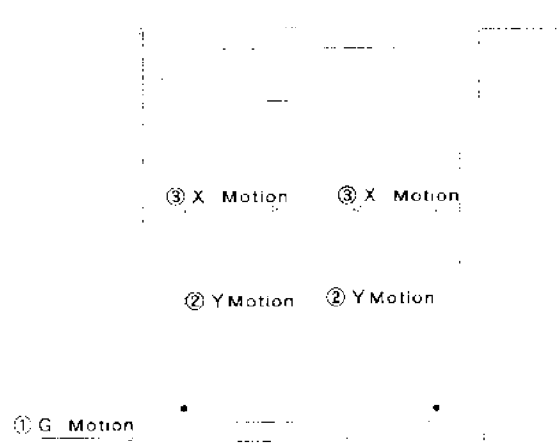

Figure 9 Robot access motion sequence.

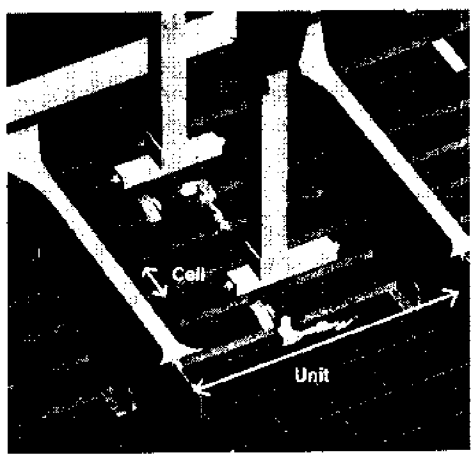

Figure 10 Typical view of robot arrangement.

CAD/CAM System

Several types of CAD/CAM system have been developed and applied for 2.5 dimensional panel shaped work in sub-assembly stage of steel bridge fabrication[3] and shipbuilding[1]. Various kinds of subjects has been addressed in the development of 3 dimensional CAD/CAM system. Robot simulator based integrated CAD/CAM system has been developed for curved block assembly. Figure 11 shows the configuration of CAD/CAM system.

CAD System

The processing flow in the CAD system is shown in Figure 12. An example of CAD output is shown in Figure 13.

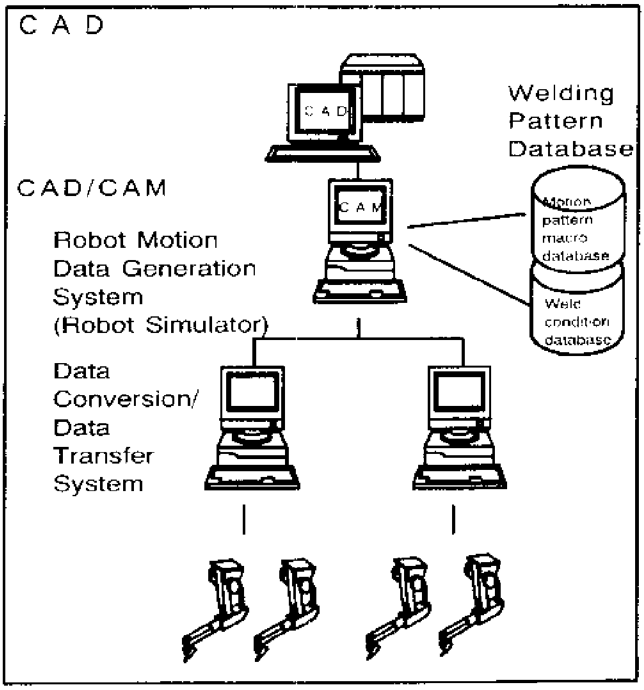

Figure 11 Configuration of CAD/CAM system.

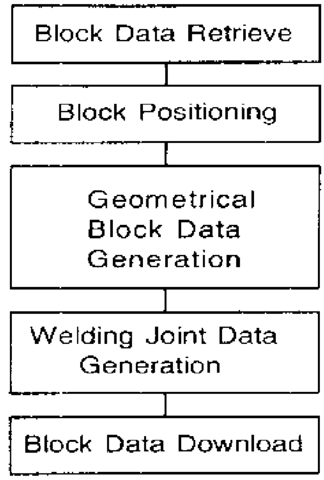

Figure 12 Processing flow in CAD system.

Block data retrieve: Geometrical information and welding information are retrieved for objective block from CAD database.
Block positioning: Optimum block positioning are decided to keep minimum block slope.
Geometrical block data generation: Geometrical data of structural member of the block are generated. Outline configuration and surface element data are generated.
Welding joint data generation: Data generation of welding joint location and its welding design data i.e. required leg length.
Data download : Geometrical information and welding information are downloaded into CAD/CAM system.

CAD/CAM System

The automatic robot programming system has been developed as CAD/CAM system. The processing flow in CAD/CAM system is shown in Figure 14.

__Work Model Generation__

3 dimensional geometrical work model are reconstructed in CAD/CAM system by using geometrical information from CAD. Several processing are added in order to compensate the work modeling. For

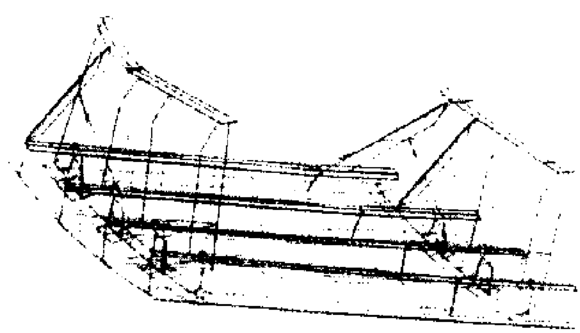

Figure 13 Output example of curved block from CAD.

instance, the configuration data is downloaded only for front side of the structural member. Then, the CAD/CAM system generates the outline geometry and surface element for the back side.

Welding Model Generation

The welding model is defined as the information model for welding operation. The welding joint information is appended on the work model. Each welding joint geometrical data are linked to the structural configuration data of stiffener, also, the welding joint recognizes the opposite workpiece in the welding model. Then, connecting and dividing processes of welding joint data is taken. In the case where the welding joints data are separated on a stiffener cause of the CAD data generation, these welding joints data must be connected as one welding joint data. On the other hand, the welding joint on a longitudinal stiffener must be divided into several joints at the cross section of transverse panel. These kinds of simple collision avoidance are processed in the modeling. Furthermore, intermediate teaching points are generated on each welding joint with a span of required slope angle. These points are used as the guide point for changing of welding condition. Finally, basic welding joint data are stored in the welding model.

The mathematical-physical robot model for collision avoidance and simulation has been priorly installed.

Collision Avoidance

Collision avoidance system has been developed for the complex structure especially in corner section. Firstly, the collision point is calculated with 2.5 dimensional geometrical check between welding torch and workpiece. Secondly, welding torch angle is defined according to the crossing angle between workpiecs at the corner section. Finally, recursive robot simulation check is taken for the detail collision avoidance. Furthermore, the pose of articulated robot is defined according to the geometric parameter at the corner section of work for collision avoidance.

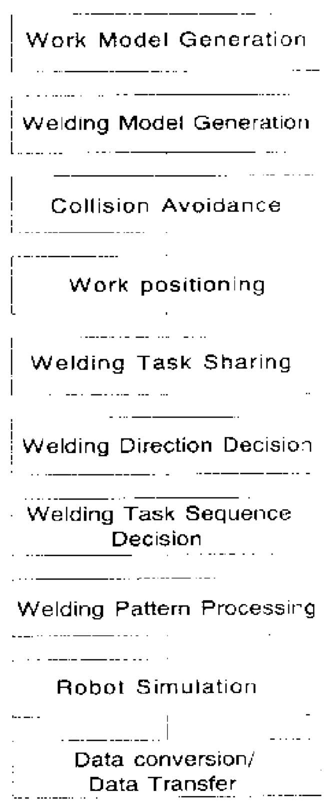

Figure 14 CAD/CAM Processing flow

Work Positioning

As optimizing of work positioning for minimum joint slope has been already determined in CAD system, work positioning i.e. work arrangement to X-Y direction is defined with graphical user interface by CAD/CAM operator.

Welding Task Sharing

The work is composed of several trans.-spaces shared by the transverse panels. Then, welding tasks are shared with several groups corresponding with the trans.-spaces. Two sets of welding robot share the welding tasks in each space. It is due to the mechanical arrangement of robots mentioned. Also, all of the welding tasks in a lattice cell are assigned to one robot as a sharing rule.

Welding direction decision

Welding direction is very important welding parameter in slope welding. Up-slope and vertical-up fillet welding are selected. Then, The CAM system defines the welding torch direction by height checking of each edge point in the welding joint.

Welding Task Sequence decision

Welding task sequence is simplified. Welding operations are carried out from left lattice cell to right one. As concerned with welding sequence in the lattice cell, vertical fillet weldings are done firstly, then slope fillet weldings follow. CAD/CAM system allows the operator to change several kinds of system parameters as to the welding sequences.

Welding Pattern Processing

The basic welding motions are stored as the welding procedure pattern in the database. Welding condition data is linked with this welding pattern. Figure 15 shows an example of welding pattern. There are 10 off-line teaching points used for edge part of collar plate. The instruction consists of torch position data (X,Y,Z), torch angle (α, β, γ) and sequence command like welding condition data. These kind of welding procedure patterns are practical knowledge base of welding expert based on laboratory's experiments.

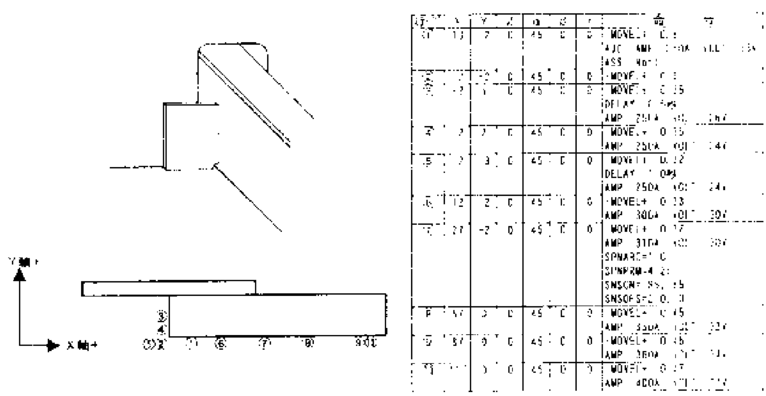

Figure 15 Example of welding pattern stored in CAD/CAM.

Robot Simulation

The robot simulator compiles above mentioned instructions into robot program. Automatic collision check between robot and workpiece is carried out concurrently. The collision occurred points are listed. After the automatic simulation, the operator corrects the robot pose and torch angle through graphic user interface. Figure 16 shows an example of robot simulation.

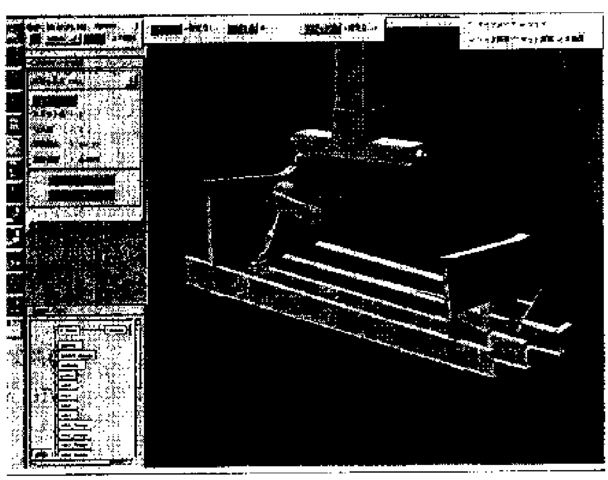

Figure 16 Example of robot simulation.

Data conversion/Data Transfer

Generated robot programs are recompiled to NC codes in the FA computer, then transferred to each welding robot controller.

Sensing System

Work Position Sensing

Laser sensor system has been developed to compensate the work positioning error. A pair of laser sensor mounted on the 2 diagonal robots detects the real work location. Coordinates transformation is carried out in the gantry controller as shown in Figure 17. Consequently, robot positioning data are correct.

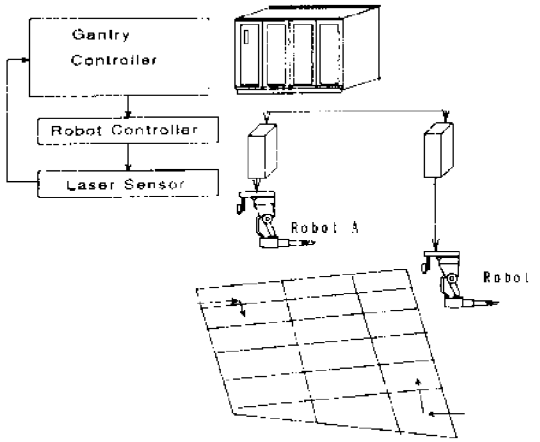

Fig 17 Coordinates transformation system.

Welding Joint Position Sensing

Wire touch sensing system is equipped in each robot controller. Both arc start point and arc end point are previously detected by wire touch sensor before welding.

Seam Tracking

Arc sensor system is equipped in each robot controller for both seam tracking and torch height control. High Speed Rotating Arc Sensor is applied for the slope fillet welding with its high reliability. Conventional weaving arc sensor is also applied for the vertical fillet welding.

Adaptive Welding Parameter Control System

Root Gap Sensing

CCD vision sensor and laser sensor are recently popular for detection of groove configuration. However, attached sensor device on the robot arm often causes problems, e.g. collision occurrence at the corner section of complex work. Developed High Speed Rotating Arc sensor never needs peripheral devices, and the control becomes more simple. Figure 18 and Figure 19 show the principle of root gap detection with HSRA. In the case of gap opening, arc voltage increases at the rear part (Cr) of each rotation in comparison with smaller gap condition, because the molten pool penetrates into the gap and results decreased bead height. Then, the summation of deviation area has a good correlation with gap opening change.

Adaptive Welding Parameter Control

Figure 20 shows the block diagram of adaptive welding parameter control. Fuzzy inference is applied for the control of non-linear correlation. Firstly, initial joint conditions are downloaded into welding parameter database from CAD/CAM system, i.e. slope angles of arc start point (θ L : slope angle of longitudinal welding direction, θ T : slope angle of transverse direction) and leg length of the welding joint. Secondly, initial welding parameters (welding current, welding voltage, welding speed) is output to welding robot controller. Other parameters for adaptive control (SGref: reference value for arc voltage wave-form, WG: root gap) is also set. After welding start, the integrator detect the deviation of arc voltage wave-form (Δ SG), the fuzzy controller estimates the change of root gap based on ΔSG value. The estimated root gap change is added to initial gap value, consequently, root gap (WG) is estimated, Then, optimum welding parameters are downloaded according to the recognized gap value. Figure 21 shows an example of experimental results of adaptive welding control. The experimental conditions are: slope angle; θ L=20° (up-slope), θ T=-20° (overhead), initial gap opening 1~6mm, required fillet size; 6 mm.

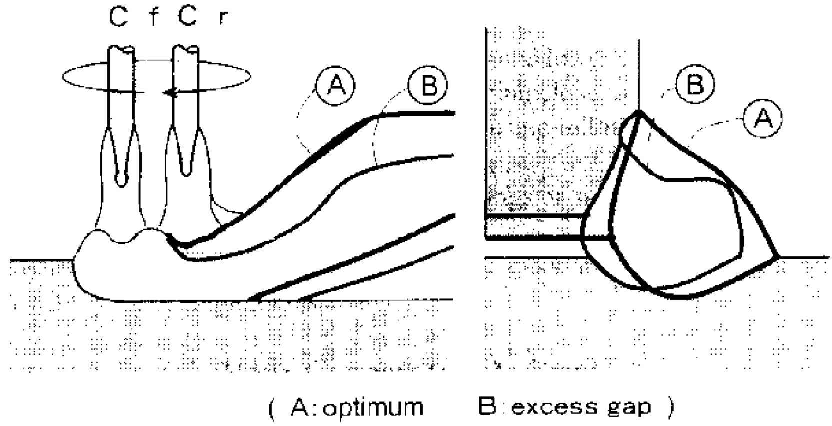

Figure 18 Principle of root gap detection

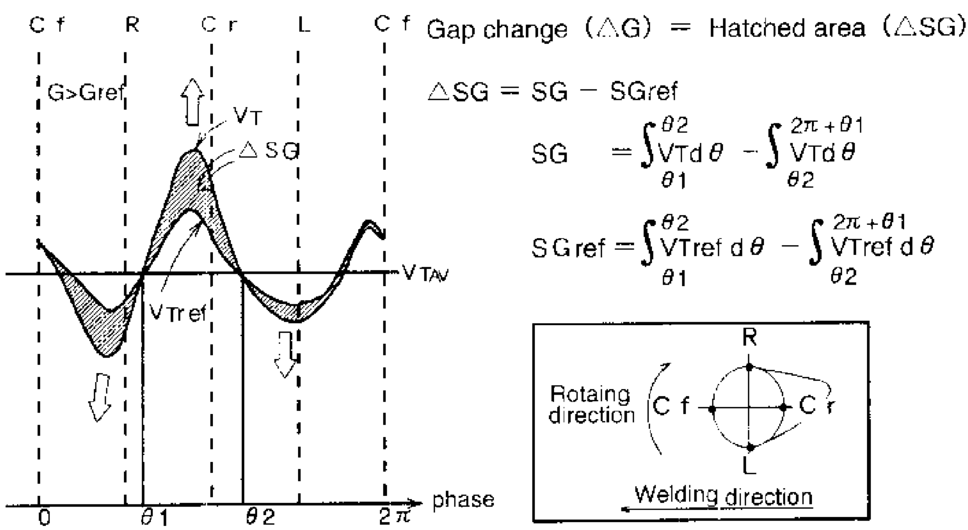

Figure 19 Principle of root gap detection

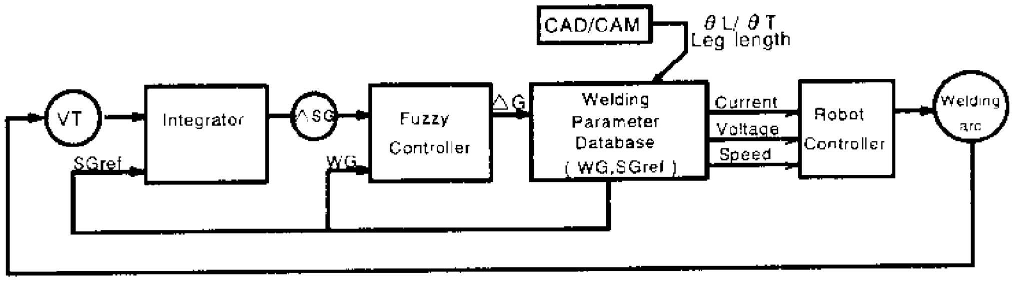

Figure 20 Adaptive control of welding parameter.

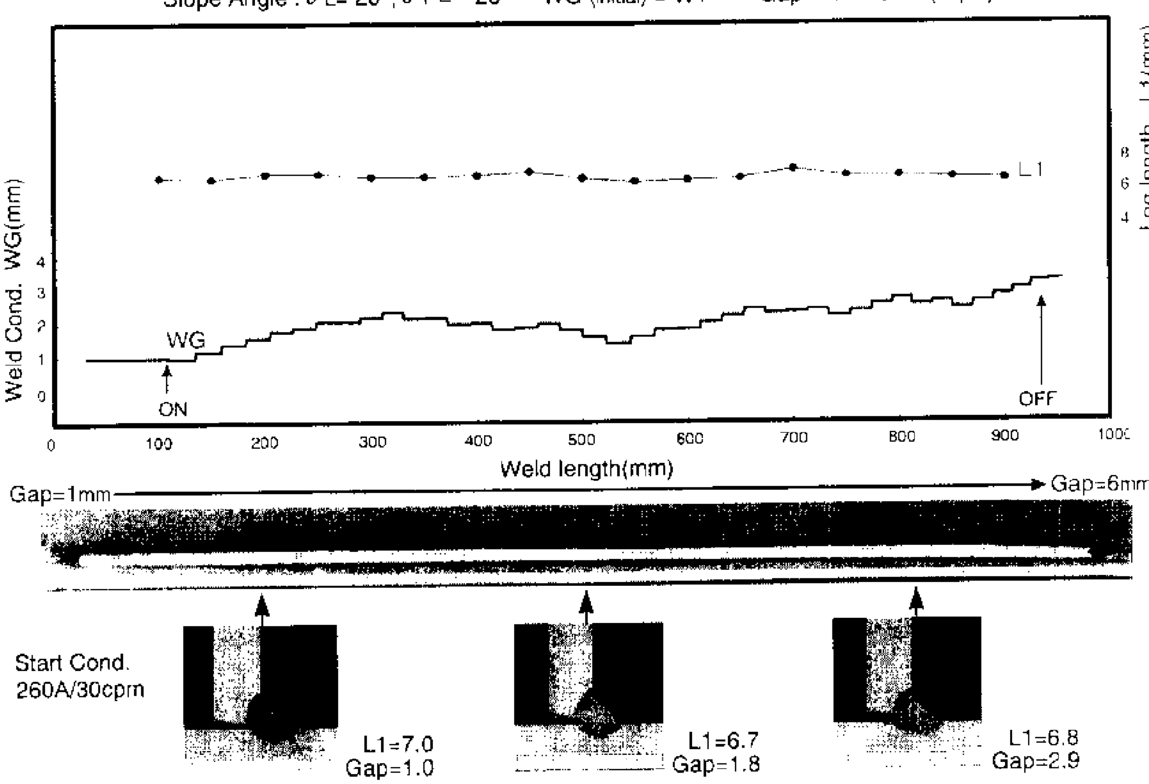

Figure 21 Experimental results of adaptive welding parameter control system.

Application

The developed multi-robot welding system has been installed into the assembly stage. Figure 22 shows a view of mock-up welding trial for curved block assembly. Figure 23 shows a view of practical trial for large scaled block assembly. The system has reached the phase of real application for the large scaled curved shell blocks.

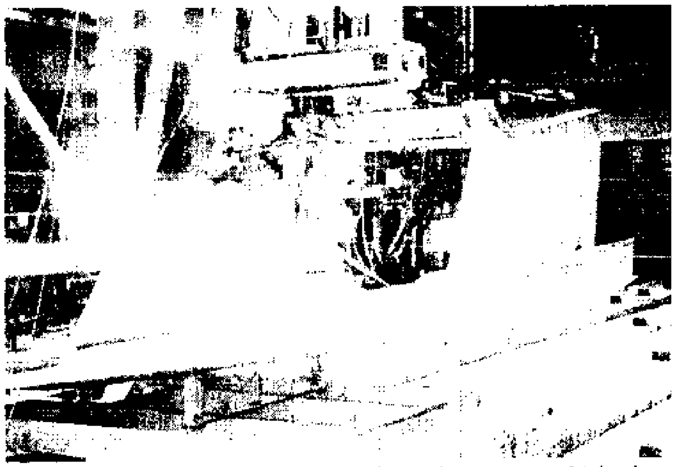
Figure 22 Application view of mock-up curved block.

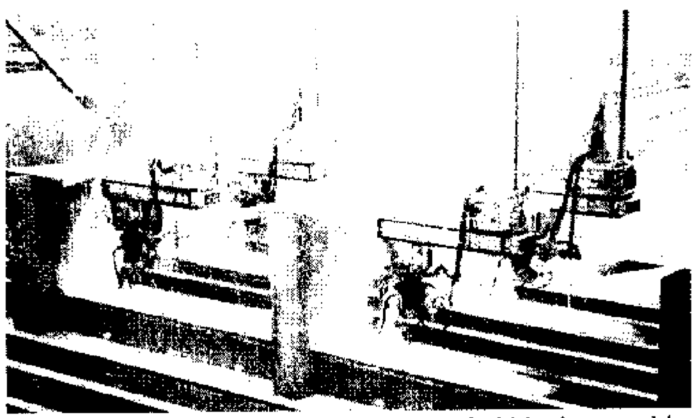
Figure 23 Application view of large scaled block assembly.

Conclusion

Multi-Robot CAD/CAM welding system has been developed for curved shell block in shipbuilding in 1998. The system consists of CAD/CAM system, multi-robot control system, adaptive welding control system and gantry type multi-robot mechanism. The feature of the welding system is as follows.

(1) Four sets of articulated welding robot with plural cartesian external axes hung from mobile large gantry as a multi-robot mechanism.
(2) Integrated CAD/CAM system generates robot program automatically. The system includes automatic collision avoidance process for complex work supported with graphical user interface.
(3) Two series of robot control are installed, i.e. gantry control for robot positioning, articulated robot motion control for welding operation. All of the control data are downloaded as a robot program.
(4) As for the Knowledge base in CAD/CAM, welding pattern database has been built for welding expert.
(5) High Speed Rotating Arc detects the root gap opening in real time for slope fillet joint. Adaptive welding parameter control is carried out with fuzzy inference. Optimum welding conditions for real gap value and slope value are controlled in real time with the database in the adaptive welding controller.
(6) The system has been successfully applied for mock-up blocks and large scaled practical block assembly. The system has reached the phase of real application for curved shell blocks.

Acknowledgements

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AUTOMATING ROBOTIC ARC WELDING IN SHIPYARD PANEL SHOPS USING A VIRTUAL ENVIRONMENT

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Abstract

The purpose of this paper is to present a methodology and tools for the automation of the process design and programming of robots performing arc-welding to assemble constructions in the shipyard panel shop. This methodology and tools were implemented as a software product in Tecnomatix Technologies Ltd. ROBCAD product line. The methodology applies to panel-shops with robotic installations of 6DOF(*Degrees Of Freedom*) welding robots mounted on 3DOF gantry systems. The pre-requisite for using the proposed methodology is having the construction geometry in a digital format.

The engineering tasks of process design and robot programming are done in a virtual environment where all decisions and planned actions are simulated to feed back feasibility and implications. The methodology covers five steps of the following process:

1. **Assembly Study:** Analysis of assemblies and parts in the construction of subassemblies and defining which parts require welding to each other.
2. **Trajectory Placing:** Creating the trajectory for the welding torch for each weld and for each search routine.
3. **Motion Placing**: Creating a collision free motion plan for the automation system to perform all welds and search routines. Such a system may consists of one or more robots each attached to a gantry system.
4. **Sequencing**: Sequencing the welding actions and creating collision free motion plans for the automation system to move from one step to the next.
5. **Programming**: Creating programs for the automation system to perform required tasks.

The objective of the proposed methodology is to support calculations and decisions.

- Calculations: Most of them are easy for the computer but difficult for a human being.
- Decisions: Most of them are difficult for a computer but easy for KNOWLEDGABLE engineers.

The project shows that by formulating the decisions required for the welding job in the panel shop, a computer system can acquire the necessary knowledge from its user and take decisions similar to the user. The proposed method narrows down the list of decisions to those required in the shipyard panel shop. This makes the actual implementation of the methodology in the software quite easy to use and practical.

Implementation of this method was done on the virtual reality platform developed by Tecnomatix Technologies Ltd. and it is available as a commercial product. The platform includes engines for 3D graphics, modeling, motion planning and user interface. Therefore, the paper concentrates on the part of the product that is specific to shipbuilding application.

Robotic Off-Line Programming

Developing software for off-line programming of robots has been a major activity in Tecnomatix Technologies Ltd. since 1985. The first software tools developed were post processors converting graphical information into robot programs. During the years, the direction has always been toward removing unnecessary loads from system users by doing necessary calculations and taking required decisions for them. The differentiation among the different users involved and their specific needs, resulted in a variety of applications which led to a complete product line. Each product in the ROBCAD product line is trying to embed the knowledge of engineering processes taking place in different applications and disciplines. ROBCAD/Arc is designated for off-line programming of arc-welding robots. It provides tools to build any kind of robotic arc-welding program. A user of this product can perform all of the following actions:

1. Define welding seams by pointing out their geometry tracks.
2. Define touch sensing (search) routines by pointing at the walls to be touched.
3. Define welding parameter per each motion step of the robot.
4. Balance the motion of the redundant kinematics chain as necessary.
5. Simulate the system motion.
6. Detect collision during motion.

This environment is effective in robotic program production where the welded geometry is small and complicated, and robots are expected to weld large batches of the same part. However, in cases where the welded part is unique and large, such as in shipbuilding, the productivity of such methodology is reduced.

The ROBCAD/Arc product uses a technological infrastructure, which is made available for the research presented here. It includes engines for direct and inverse kinematics, 3D modeling, 3D graphic display and manipulation, collision detection, and basic motion planning as well as simulation. Algorithms used out of this infrastructure are not presented in this paper and all sources used in the different research conducted to develop those algorithms are not referenced here.

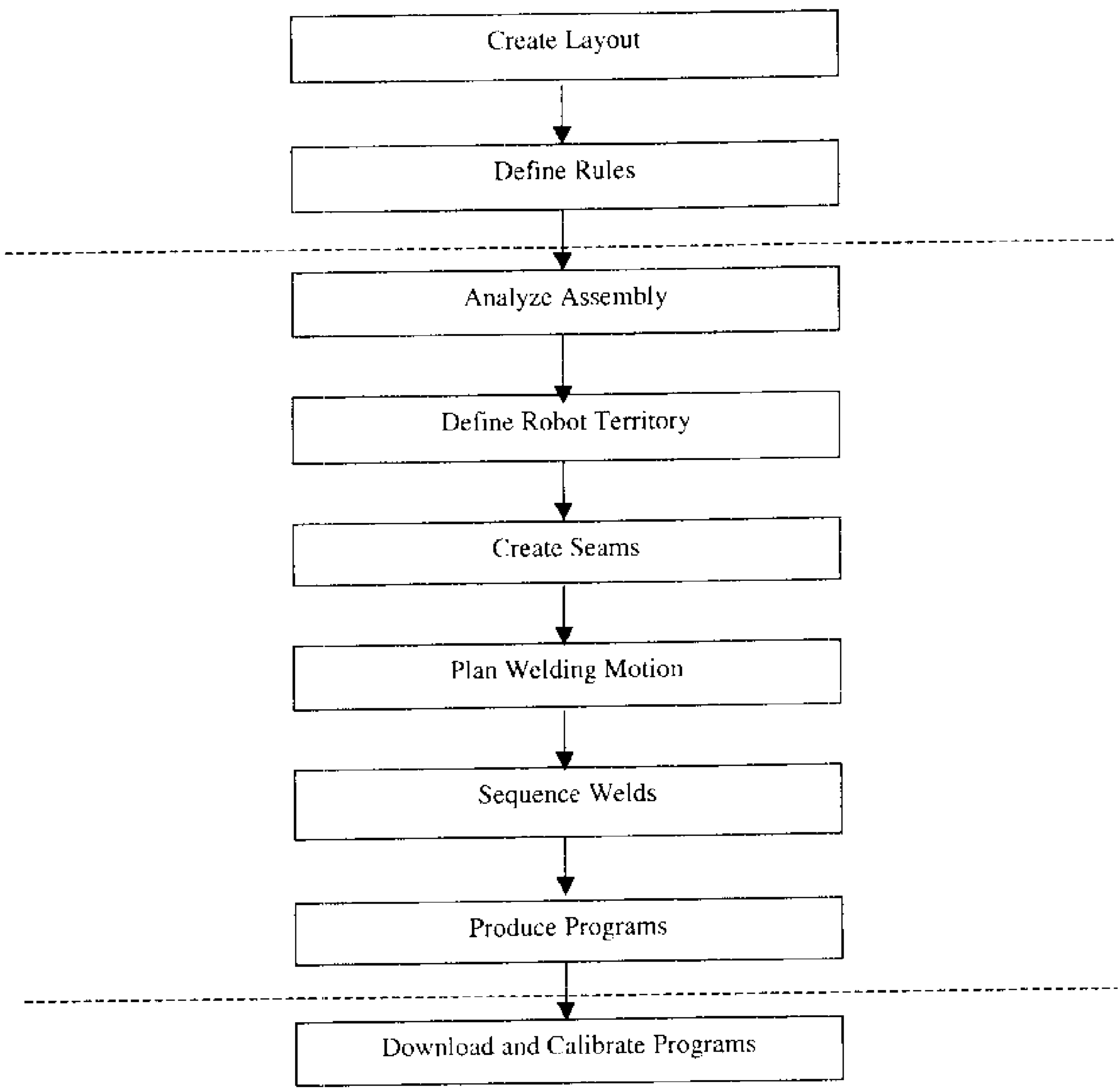
The System Objective

The objective defined for the authors was to develop a software that accelerates the process of creating robotic programs for arc welding robots in a typical panel-shop of a shipyard. Such acceleration can be achieved by automating the currently known process of programming. User intervention has to be reduced to a minimum and algorithms implemented in the system must be efficient and fast.

The typical panel-shop that we have considered consists of a number of 6DOF robots mounted on 3DOF gantry systems where each robot can control his gantry system independently. The size of the space where the construction takes place is 10m high, 10m wide and 25 meters long. Please refer to **Figure 1** below for a diagram of a panel shop.

The quantitative requirement from the system was based on existing practices in a typical panel-shop. Each construction is one of a kind and the programming job required for the welding is dedicated to each construction. In order to have an efficient workflow in the shop it is necessary the program is created within a period of time that is shorter than the actual welding time of each construction.

Figure 1. A Typical Panel-Shop



General Approach

From the onset it was clear that a conceptual upgrade would be required for each and every capability of ROBCAD/Arc. The following is a list of required capabilities for each programming job supported in the ROBCAD/Arc product and necessary in the new system but in a totally different way:

1. Creation of seams should not be based on the user identifying start and end points. Tracks must be identified out of construction geometry automatically.
2. Touch sensing (search) routines should not be created by the user pointing at the touched walls. These walls must be automatically identified as the walls closest to the given seam.
3. Welding parameters should not be defined by the user for each robot motion or welding seam. These parameters must be defined automatically according to geometry and other known conditions.
4. Balance of motion between the robot and the gantry system should not be left for the user to define. It has to be found by the system in a way that will provide the most efficient and smooth motion.
5. Collisions should not be detected. They should be avoided.

The set of decisions taken by a skilled person that is creating a robotic program of the kind we are looking at is quite clear and easy to understand. There is a very structured process with distinctive straightforward steps. The difficult part is the know-how behind each decision. The Shipyard industry works according to know-how that has been accumulated over hundreds of years. This know-how shows the way to consider information and take decisions accordingly. (*The term know-how is defined in this paper as both accumulated engineering knowledge expertise as well as intuitiveness gained through experience.*) The people running the panel-shop obtain and consider information relevant to necessary decision making. Some of the considerations are well defined and some are taken based on expertise. As a general rule we have decided to base the system on the following approach:

- The system will take decisions automatically.
- The way to consider information and get to a decision will be defined by the users in a general manner by determining the values of a set of predefined parameters.
- The required information will be the digital model of the panel-shop and the welded construction.

The above general rule implies a certain structure to the system. Primarily there is a structural environment in which the model of the shop and constructions are built; there is also another environment where programs are created. The system being described in this paper is the second part focused on program creation where every action of the system starts with analysis of user know-how and ends with running general algorithms. The environment and tools for modeling the shop, assigning kinematic characteristics to the robots and gantry, and reading the construction information from CAD databases is part of the basic ROBCAD system and is not described here. Another part of the system that is not described in detail in this paper is the process of downloading the programs and calibrating them. Again, these are standard capabilities of the ROBCAD system and are not developed within the framework of this research.

System Structure

System Architecture

The system blocks are presented here as matching the recommended sequence of steps performed by the user. The sequence is described below in **Figure 2** and each one of the steps is described with association to the relevant software block.

Figure 2. User Sequence of Steps

Creating the Layout

Creating the digital layout of the shop consists of several actions. All standard equipment like industrial robots is available for retrieval in the data library. Special equipment can be built either in a CAD system or in the modeling tools of the system. The ship construction is retrieved from the CAD system it is built in. Once the layout is set, the whole panel-shop can be displayed and viewed on the screen. The automation system can then be manipulated according to the *Degrees Of Freedom* defined.

Defining the Rules

The welding process know-how of the user is formulated by simply assigning values to a list of parameters. These parameters will control the decisions made by the system later on in the process. Some of the parameters are listed below:

- Approach and depart angles according to weld type
- Shape of welding ends
- Direction of vertical welding (up or down) according to metal thickness
- Balance of robot and gantry motion according to weld length
- Search parameters
- First guess for best robot position for different welds
- Priority of directions to avoid collisions by the robot
- Welding parameters according to different conditions (direction, thickness, etc.)
- Allowed gap between welded walls

Analyzing the Assembly

The ship constructions are designed in a CAD system. As in other assemblies designed on CAD, the designers build the assembly tree in a way that follows the logic of the design. An assembly usually represents either a certain geographic area of the whole ship, or a certain functional zone or block within the ship. Subassemblies are built the same way, following the top-down process of design.

The assembly tree for the assembly process is different than the one for the production process. Here, a subassembly is part of the ship that has been manufactured or assembled in a certain shop. The decisions on assembly order come from different considerations such as equipment requirements and space allocation needs. These decisions usually lead to a different assembly tree than the one defined by the designer. This manufacturing information is built into the CAD model by different methods like naming conventions and attributes attached to the geometry.

In this part of the system there is an analysis performed on the construction data in order to understand where the welds are required. It automatically distinguishes which parts are already welded together, and which parts are not intended for welding at all. This analysis is performed according to the specific method chosen by the user to define the manufacturing assembly tree.

Defining Robot Work Spaces

As the system should support multiple robot installations, it is necessary to allocate space for each robot to work. This helps to avoid collision between the different robots working together and maps the whole space in a way that helps managing the huge task of programming hundreds of meters of seams. The space is defined either as a box including the volume of welds programmed for a certain robot, or by pointing out the subassemblies to be considered for this certain part of the programming job.

Creating the Seams

When the pieces to be welded in the active space are pointed out, the algorithm for defining the seams can be activated. This algorithm works through the following steps:

- Find all touching pairs of walls. Touching means closer than the allowed gap size. This step delivers a list of lines along which welds should be performed.
- Find all places where welds should go along as few consecutive lines, and merge the consecutive lines.
- Find all places where obstacles prevent the automation system from performing the weld. Wherever such an obstacle is identified, the lines are divided into two welds. Each line can be approached from another side of the obstacle. Such division of one line into two welding seams is represented in **Figure 3** below. This part of the algorithm uses ray-tracing methods as described in Badouel[1] and Woo[2].
- Classify the seams according to wall thickness, length, and type of geometry at both ends.
- Decide on the direction of each seam.
- Define start and end sections of each weld in terms of torch direction, distance of edge and changes of torch direction.
- Assign welding parameters to each weld according to all known parameters.
- Create touch sensing (search) routines for the seams.

Figure 3. Dividing One Line Into Two Seams

Planning the Welding Motion

In order to weld the seams created in the previous step, it is required to define the position of the gantry system during the performance of the welding. The gantry system is used to get the robot to the specified welding area. The robot has to be positioned in such a way so that its motion will not go through singular points. According to the seam length, the system will decide how to use the gantry. If it is a short seam, the gantry will be set in one position along the welding of the whole seam. In the case of long seams, the system will set the gantry in one position for the starting section and in another position for the ending section. This redundant kinematic chain is manipulated in order to get motion that will be free of all collisions. As there are multiple solutions to satisfy the requirements at this step, we rely on user know-how to make an initial educated guess for establishing the gantry position. This position will allow the robot to be in a configuration defined by the user configuration. The result is a set of motions performed by the gantry and robot. These motions not only satisfy the well defined rules, but also make sense for the experienced welding engineers that sometimes criticize robot motion for not satisfying rules that are not well defined. At this point all welding seams and search routines are defined and graphically displayed on the 3D model of the construction as shown below in **Figure 4**.

Figure 4. Graphic Display of Welding Seams and Search Routines

Sequencing the Welds

Once all welding motions are defined it is required to look at the complete job and sequence the welds to one large program We have divided this solution into three steps. First we find all approach and retract motions for all seams and search routines. Second we sort the seams and achieve an order of seams for overall efficiency. The third and final step is finding a collision free track for the robot and gantry. The robot and gantry move from a retracting motion of one seam to the approach motion of the next seam.

The first step is defining correct approach and depart motions, using the know-how of the user. The directions of where to approach from and where to retract to is dictated both by the walls around the area and the robot configuration at the start of the motion. This configuration is found with the help of the user defining first guess configurations as mentioned in the rules definition phase previously. These motions are performed within a certain space defined specifically by the surrounding walls where there is always at least one open end to the space. The system gets the robot to and from this open end of space using the gantry in cases where the space is large enough. It manipulates the robot joints in order to change the dimensions of its convex hull (Preparata and Shamos [3]) as to fit into the space. Each approach motion starts in a space that resides above the construction. This is also the space where all retract motions end.

The second step of sequencing, is done by sorting the seams into groups and sequencing the seams in each group. The sort is performed according to robot configuration and direction of seams. The result is groups of seams where connecting motions between seams of each group are short in time. The sequencing in each group is done by looking for the closest start point to each end point of welding motions. (Halperin and Sharir[4])

The third and last step of connecting a retract motion to the next approach is very simple. As all connecting motions are in an area above the constructions, linear motions can be used without causing collisions. (Qin, Cameron and McLean[5].)

As the algorithms for finding motion between seams does not strictly eliminate the possibility of collision, each motion is simulated internally and uses the collision detection engine of the ROBCAD platform. Collisions are detected and the motion is corrected in a short iterative loop.

Program Production

Once all welding programs are created and exist as geometrical information with attributes in the ROBCAD data format, a fast conversion is done to produce a robot program in the target robot controller language. As not every robot can interface to Cartesian coordinate targets, the ROBCAD system can calculate the inverse kinematics and communicate the joint values to the robot controller when necessary. It is also possible, at this point, to ask the robot to perform different routines that depend on total length of motion or welding. These routines are inserted in the program in the appropriate place.

Downloading and Calibrating Programs

A complete robot program is at this point sent to the robot controller. After a calibration process that makes sure the digital model and the real layout are identical, the automation system is ready to move.

Results and Conclusions

The most important result is that this developed system can create welding programs in a shorter time than the actual welding takes. The implication is that a panel-shop can work around the clock three shifts a day without downtime for programming while one operator can create programs for welding the constructions, thus increasing throughput of the panel shop.

Another general finding of the research is the performance boost we were able to demonstrate by using user know-how as a hint for first guesses in the decisions made. This finding was consistent throughout the different algorithms implemented in the system. Many decision making algorithms were implemented at the first round as general algorithms. Significant improvement in performance was demonstrated each time the algorithm was given user rules as an aid in decision making. This implies the best methodology should rely on human experts rather than replace them.

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DEVELOPMENT OF A MULTI-ROBOT WELDING SYSTEM FOR SUBASSEMBLY STAGES IN SHIPBUILDING

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Introduction

As one of the means to improve productivity in the shipbuilding industry, the development of CIMS (Computer Integrated Manufacturing Systems) has been promoted aggressively. In production factories, cost reduction using robot welding systems has already become practicable, utilizing structural data and production data produced by three-dimensional CAD systems [1].

Although a twin-robot welding system for subassembly linked with a three dimensional CAD system had been used for production at our Sakaide Works [2], the system has limitations about the structure of workpieces such as their size, the configuration and positioning of parts, and motions of the robots.

Accordingly, in February 1998, a new multi-robot welding system with hardly any of these restrictions, for general large-size three-dimensional subassemblies, linked with a three-dimensional CAD system, was developed and put into practical use. This is a group-controlled robot system in which a multiple number of robots perform simultaneous welding on several workpieces without human monitoring. In developing this system, the focus was placed not only on the establishment of group control techniques, but also on minimizing the stand-by time to avoid interference among robots to maximize productivity, and also on giving flexibility in generating the production lot data.

This system has been operated successfully in our Sakaide Works and the expected cost reduction has been achieved.

Overview of the System

Work Performed

Workpieces processed by this system are subassemblies of a hull, consisting of flat plates with stiffeners, brackets, faceplates and other stiffening materials attached as shown in **Figure 1**. Joints welded by this system are of the fillet welded type (including joints welded with an angle of other than 90 degrees) in a horizontal position, and

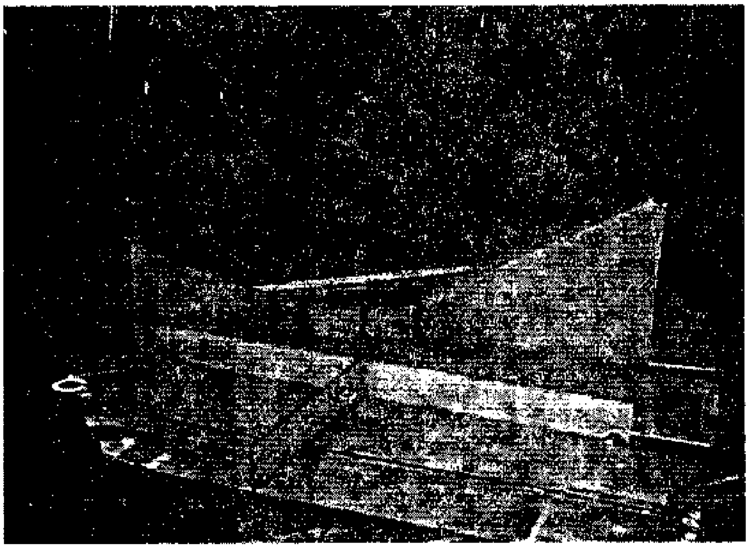

Figure 1 An Example of a Workpiece

fillet welded type (including joints welded with an angle of other than 90 degrees) in a vertical position of vertically or diagonally crossed parts. Weld lines covered by this system are straight lines, arc lines and combinations of thereof.

System Configuration

As shown in **Figure 2**, the system is composed of four gantry-type moving units with four external axes; longitudinal, lateral, vertical and rotational. Its moving units travel along the same

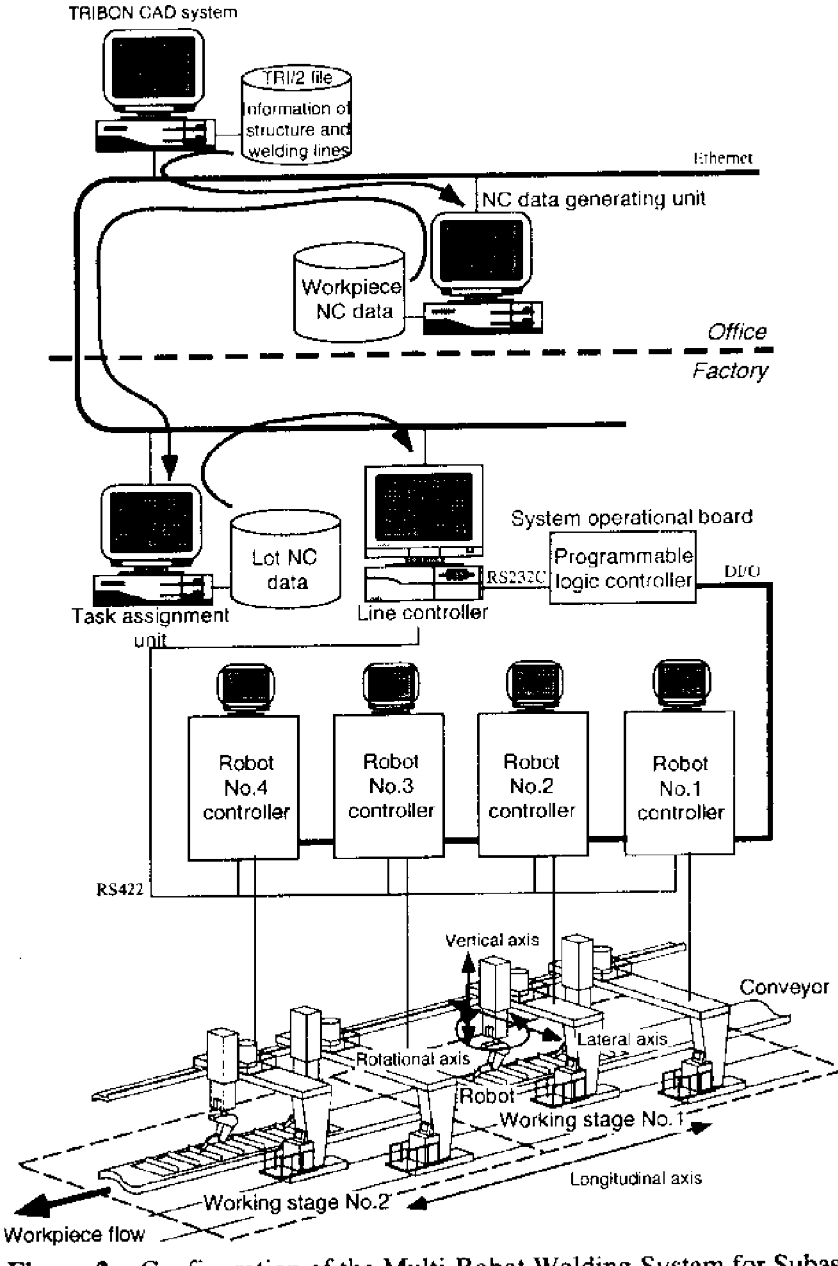

Figure 2 Configuration of the Multi-Robot Welding System for Subassembly

track. A six-joint robot suspended perpendicularly from each moving unit has a welding torch at the end of its arm, and the four robots simultaneously perform assigned welding tasks on a multiple number of workpieces.

Data flow in the system is as follows:

1. At the production design office, an NC (numerical control) data generating unit reads a TRI/2 (**TRIBON** Robot Interface/2) file output from **TRIBON**, a three-dimensional CAD system for hull design.
2. It generates NC data necessary for welding individual workpieces.
3. At a production site a task assignment unit assigns robots to each workpiece positioned on an upstream conveyor (Tack-Welding Stage).
4. It transfers the NC data for each lot to a line controller.
5. The line controller measures the position of the multiple number of workpieces simultaneously carried by a conveyor, using ITVs (industrial televisions) attached to the robots.
6. Based on the measurement, the NC data for the robots is adjusted.
7. The line controller transfers the adjusted NC data to each robot controller, which activates the robot, thereby managing and controlling the four robots to avoid mutual interference.

Characteristics

This system has the following characteristics.

(1) It has an off-line teachless system that automatically generates robot NC data, utilizing the design data output from **TRIBON**. Therefore, it does not require a direct teaching process in which robots are actually moved on the production site to teach the required movements. The system also has a function to adjust the NC data based on the detection of the position of workpieces through ITVs and connecting points of parts by touch sensing.

(2) NC data for each lot can be generated on desired timing for a multiple number of workpieces positioned on the conveyor at the production site.

(3) Since four robots perform welding simultaneously, high productivity can be achieved. To this end, the workload for each robot is equalized and the stand-by time to avoid interference between adjoining robots has to be reduced. In order to achieve these, a work area for a lot is divided into four areas and the welding tasks are done in two stages as shown in **Figure 3**. The two of four areas are processed by Robot Nos. 1 and 2 in Working Stage No.1, the rest are processed by Robot Nos. 3 and 4 in Working Stage No.2. As a result, interference between adjoining robots is minimized.

(4) The hyper-arc welding method with the arc welding torch rotated at high speed used in this system enables high speed welding with high current. The accuracy of tracking of welding paths is greatly improved by the hyper-arc sensing. Also air cut time is significantly shortened by the hyper-arc sensing to replace the conventional touch sensing, which detects the rear end of parts, bead connecting and obstacles.

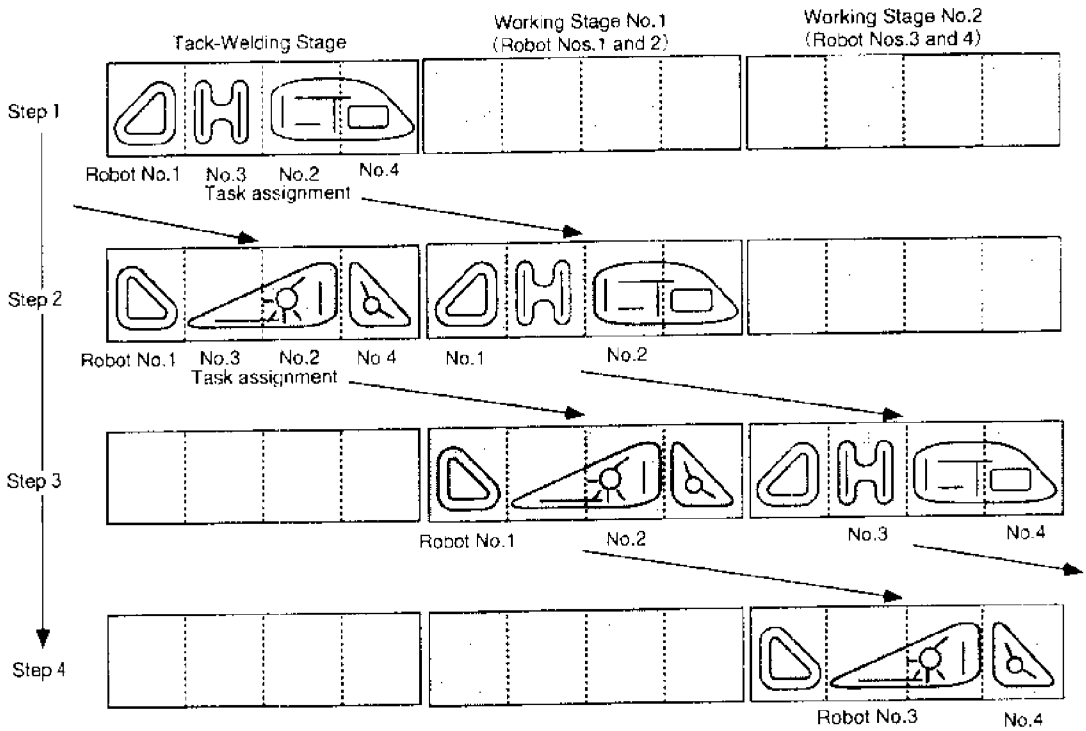

Figure 3 Task Assignment Method for Each Robot

NC Data Generating Unit

This unit generates the NC data used by robots for each workpiece, using the structural and weld line data (TRI/2 file) from **TRIBON**. The steps for NC data generation are shown in **Figure 4** [3]. Function (1) is executed automatically by the computer, and other functions are executed automatically or by an operator as required.

(1) CAD data read function

This is a function to extract three-dimensional configuration data and welding-related data for workpieces from TRI/2 file that is output from **TRIBON**.

(2) Reference points and workpiece loading direction set function

This is a function by which the operator sets the direction in which a workpiece is loaded on a conveyor, and sets reference points using a three-dimensional viewer.

(3) Part and weld line data edit function

This is a function by which the operator makes various settings such as post attachment of parts, change of leg lengths, and areas that should be left unwelded, using a three-dimensional viewer.

(4) Work area division function

This is a function to determine the number of robots assigned to a workpiece, and to determine automatically borders dividing adjoining work areas to equalize the workload for each robot as much as possible. Although the number of robots assigned to an operation is determined automatically based on the workpiece size, the operator may change the number manually.

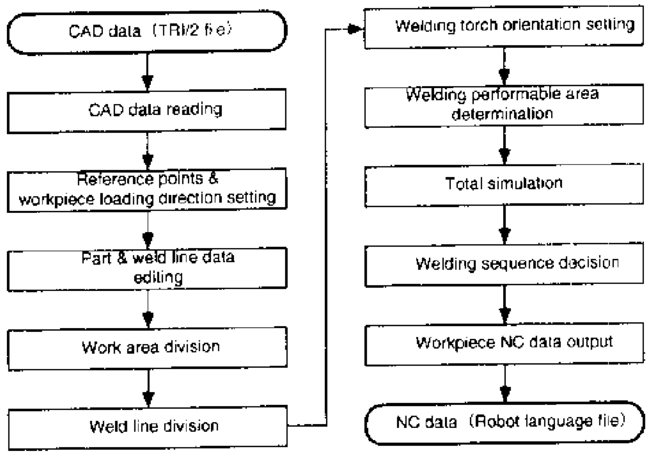

Figure 4 The Procedure for Generating NC Data

(5) Weld line division function

This is an automatic function to divide a weld line running across the determined borders into two or more sections, to find out the range where a robot cannot perform continuous welding based on the positioning of parts around the weld line, and to divide or shorten a weld line.

(6) Welding torch orientation set function

This is an automatic function to determine the welding torch orientation and the position of the external axes for each weld line. The torch orientation at the end of the weld line (whether it should be vertical or forward or backward angled against the weld line) is also determined automatically, based on the connecting angle of the part end with the adjacent part.

(7) Welding performable area determination function

By executing simulation, it can be examined whether or not a robot can take a welding position along the weld lines to determine the welding performable areas, as shown in **Figure 5**. If there is a range on a weld line where the robot cannot perform

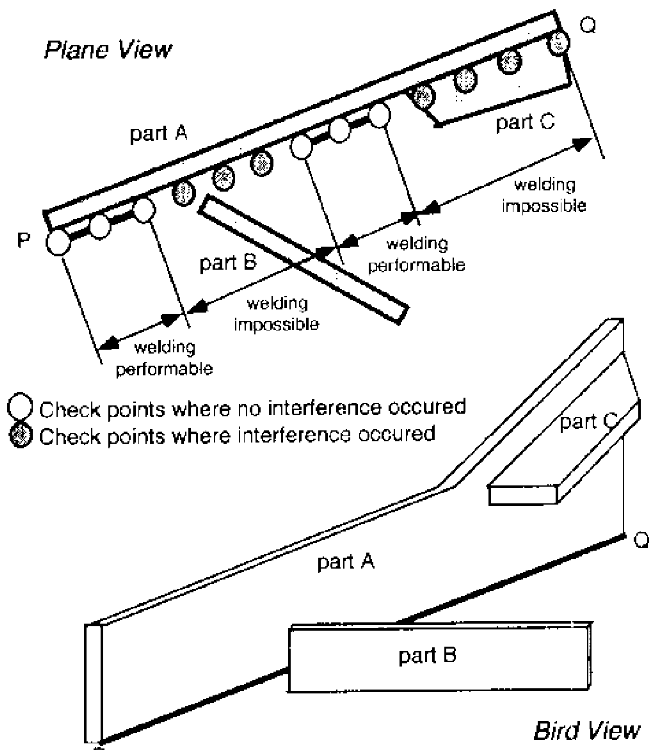

Figure 5 Welding Performable Area Determination

welding because of interfefrence, the weld line is shortened. A report of the simulation results is generated.

(8) Total simulation function

This is a function to execute a simulation to check interference along the overall robot motion path, including approach and departure movement. If interference between the robot and the surrounding parts along a weld line is detected, the system skips welding for the weld line. A report of the simulation results is generated.

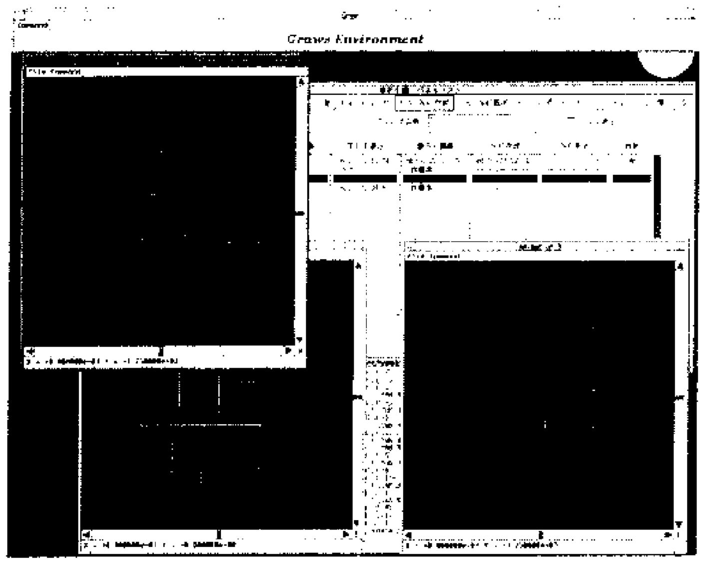

Figure 6 A Graphical Display for the Robot Simulator

(9) Welding sequence decision function

This is an automatic function to determine the welding direction and sequence for each weld line in order to minimize the air cut time.

(10) Workpiece NC data output function

This is a function to estimate workload and work hours, and output NC data for operating robots for each workpiece to a robot language format file.

Figure 6 is an example of the graphical display showing the NC data generating unit simulating robot motions.

Automatic Welding Equipment

Task Assignment Unit

This unit inputs the positions of the multiple number of workpieces positioned on the upstream conveyor to the computer, assigns the four robots to individual work areas, and generates NC data and work instructions for each production lot. The unit has four functions:

(1) Workpiece selection

This function selects NC data generated by the NC data generating unit for each workpiece.

(2) Workpiece arrangement

This function displays the workpiece arrangement set by an operator, based on the actual positions of workpieces on the conveyor. An example of the workpiece arrangement display is shown in **Figure 7**.

(3) Robot assignment

This function assigns a welding robot to each work area on the positioned workpieces .

(4) Lot NC data generation

This function generates NC data for each production lot, that is for a multiple number of workpieces positioned.

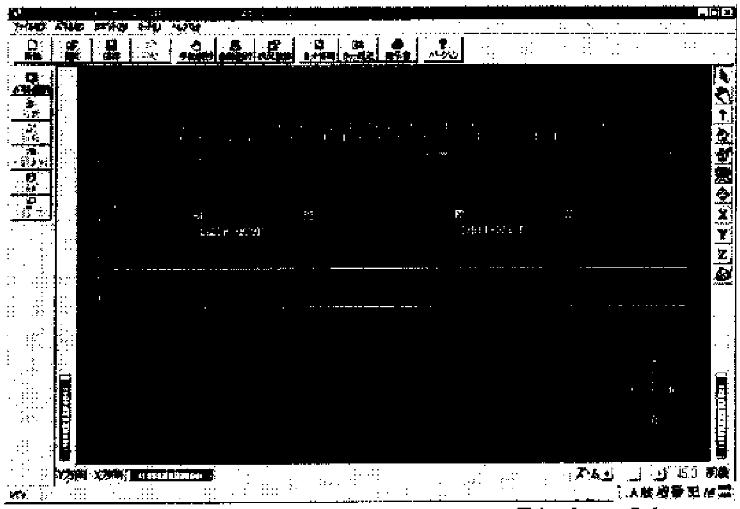

Figure 7 Workpiece Arrangement Display of the Task Assignment Unit

Line Controller

This unit manages and controls the entire production line including robots, conveyors and other peripheral units [4]. The network for the line controller is shown in **Figure 8.** When a multiple number of workpieces, to which a robot has been assigned by the task assignment unit, is carried to the work stages, the following processes are executed by the start of operation command given by an operator through the controller. First, each robot automatically measures the first and second reference points for each workpiece. This process is performed by the robots, which automatically move to the magnetic markers preset at reference points specified by the NC data generating unit. The positions of these markers are recognized via ITV cameras attached to the robots.

When all robots have completed the measuring of reference points, the coordinates of the NC data are automatically adjusted based on the detected positions by the robots. Welding is started after it has been confirmed that adjoining robots will not interfere with each other. If interference occurs, the line controller has a function to eliminate the interference by forcing one of the interfering robots

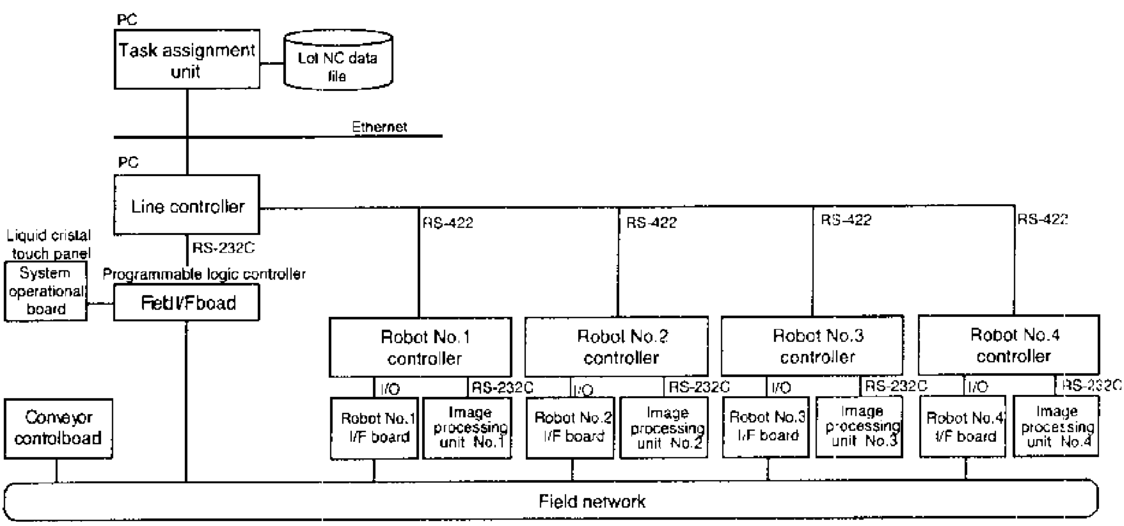

Figure 8 The Network for the Line Controller

to stand by from operating or retreat if idling. When all welding processes assigned to each robot have been completed, the robots automatically return to the origin point and the operational cycle stops. **Figure 9** shows an example of the operating screen of this unit.

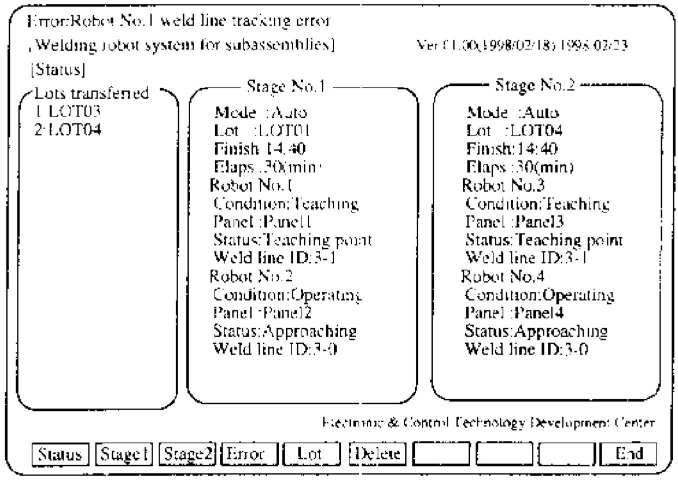

Figure 9 An Example of the Operating Screen

Welding Robot Equipment

1. <u>Composition</u>

Robots utilized in this system are the Kawasaki Heavy Industries' arc-welding robots JA-10. In the longitudinal axes of the gantry-type moving unit, carriages on the right and left sides of the gantry are driven by individual servo motors and controlled by dual servos synchronized by software. Movements of eleven axes are controlled cooperatively; 6 joints for the robot arm, two longitudinal, one lateral, one vertical and one rotational axes. By providing an outer rotational axis on the rotating axis of the six-joint robot, the continuous welding of the circumference of a large radius or complex contour has become feasible. A general view of the welding robot equipment is shown in **Figure 10**. The system can thus handle various workpieces with widely diverse configurations.

Figure 10 A General View of the Welding Robot Equipment

For a system like the one described in this paper in which a multiple number of robots perform simultaneous welding, it is necessary to enhance working efficiency by minimizing the stand-by time associated with interference between robots or the gantry-type moving unit and a robot. To achieve this, the space on the gantry-type moving unit where other units are mounted is reduced by using a compact (one-sixth the size of our traditional controller) robot controller. Furthermore, since two tracks are provided for the main carriage of the longitudinal axes, the four gantry-type moving units may be located alternately. Thus, the proximate distance between moving units can be shortened to 1.6 meters.

An inverter is used as the power source for welding, supplying a hyper-arc (high-speed rotating arc) torch equipped with a water cooling system. In addition, the equipment has a high voltage touch sensing device, nozzle cleaner and wire cutter. To eliminate factors that impede feeding of welding wire, two pail packs (welding wire feeding cans) including one extra are mounted on the lateral table on the gantry, so the length of the conduit cable is minimized.

The specifications of the welding robot equipment are shown in **Table 1**.

Table 1. Main Specifications of the Welding Robot Equipment

Items	Specifications
Robot	Four vertical, six-joint robots, Kawasaki JA-10
Moving unit	Gantry-type Longitudinal axis 16.6m Lateral axis 5.48m Vertical axis 1.5 m Rotational axis 730° (±365°)
Welding power source	600A inverter
Welding torch	Four hyper-arc welding torches Water-cooled, 500A(100%)
Sensing functions	·Touch sensing ·Weld line tracking ·Plate end detection ·Previously-made bead detection ·Obstacle detection
Reference point marker detection	K-HIPE-R (Vision sensor)
Workpiece	Panel with stiffeners and brackets Length 2,500~15,000mm Width ≦5,200mm Member height ≦1,500mm
Welding operation	·Horizontal fillet welding(Leg length 5~7mm) Line (Angle between two plates 70~110°) Circular arc(Radius ≧ 300mm) Combination of lines and circular arcs ·Horizontal fillet multi-layer welding (Leg length 8~12mm) ·Vertical fillet welding (Angle between two plates 80~110°) ·Boxing(Plate thickness ≧ 8mm)

2. Robot Motion Program

The motions of the robot are controlled by a program written in the robot language. Reference points on workpieces are automatically identified by the vision sensor, based on the NC data transferred from the line controller to the robot controllers. Based on the reference data, adjustment calculations are executed within the robot controller, and then automatic welding is executed.

By using the multi-functional teaching pendant of the robot controller, or connecting a notebook type PC, welding motions, welding conditions, and other variables may be modified on the production site to facilitate timely incorporation of the knowledge or practical demands of operators into robot motions. Accordingly, a general-purpose piece of equipment with high practicability has been achieved.

3. Welding Motion

In horizontal fillet welding, the touch sensing motions, boxing of ends, and other standard pattern motions at the ends of parts are performed only by the motion of six robot joints. During this operation the gantry-type moving units do not move. Motions for the welding of straight or curved weld lines in the central areas of parts are mainly made by the gantry-type moving unit, while the robots perform hyper-arc tracking.

Not only for single-layer welding of straight or curved lines, but also for more complex welding combinations as well as multi-layer welding, high quality continuous beads are produced by the cooperative control of the motions of all axes including the gantry-type moving unit. **Figure 11** shows a view of the cross section of multi-layer fillet welding bead.

For fillet welding performed in vertical orientations, the robot makes specially patterned weaving motions, and the movement of the gantry-type moving unit is cooperatively controlled. As a result, excellent bead appearance is obtained, including formation of the corner of lower ends of welds and boxing at upper ends in vertical fillet welding on vertically or diagonally crossed parts. **Figure 12** shows a view of the welding bead in the vertical corner of diagonally crossed parts.

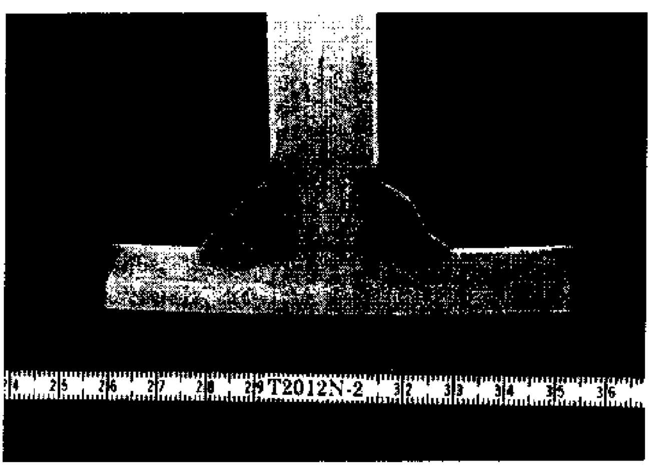

Figure 11 A View of the Cross Section of Multi-Layer Fillet Welding Beads

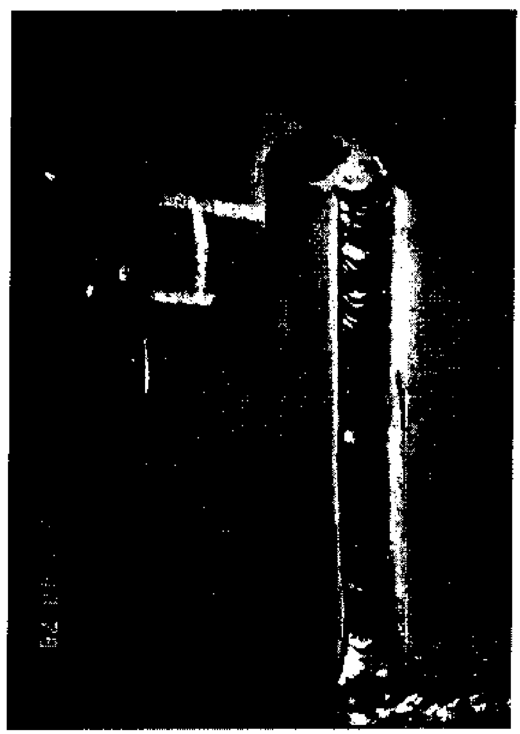

Figure 12 A View of the Welding Bead in the Vertical Corner of Diagonally Crossed Parts

Conclusions

Using an off-line teachless system where the information for robot operation is created from design data generated by **TRIBON**, a three-dimensional CAD system, we have successfully completed an automatic welding system for panel-shaped ship reinforcement members. While equipment and specifications described in the previously published paper [2] are used as the fundamentals, this system has the following features:

(1) This system does not limit the configuration of workpieces, and enables the welding of large three-dimensional subassemblies.

(2) This system does not limit the type of weld joints possible to be performed.

(3) This system has flexibility in the generation of production lot data.

Utilizing the technology that achieved the previously detailed advantages by developing a system in which a multiple number of robots may be used, and by combining further state-of-the-art technology such as group control of robots, the cost for the welding operation was dramatically reduced.

KHI (Kawasaki Heavy Industries) will continue to refine this system, based on practical knowledge obtained through actual operation, aiming to significantly improve productivity.

KHI will continue the further development and diffusion of this system since the numerical group control technology for robots which was put into practice by this system, with off-line teachless method utilizing three-dimensional CAD data, is very effective for producing a wide variety of products in short-term runs, or the production of items with such complex structures as found in the shipbuilding industry.

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ASSEMBLY WELD PLANNING FOR WORK CONTENT CALCULATION AND ROBOT CONTROL

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Abstract

In the scope of a development project for a process chain from assembly weld analysis to robot welding a new Weld Planning application has been developed. The main goals of the project were to support production engineers with precise welding information and to provide an interface to robot control systems.

The Weld Planning application program utilizes the hull structure and assembly definition from the TRIBON product model. The system supports the automatic weld analysis for assembly structures. Advanced geometric and topological analysis algorithms were developed based on the ACIS modeling kernel. Part to part, part to assembly and assembly to assembly connections are handled by these algorithms.

The weld analysis generates complete welding information including precise weld geometry and weld parameters. This includes weld length, size, position and various technical weld parameters. User defined configuration tables allow to customize the weld parameter calculations.

All welding data are handled as an integrated part of the TRIBON product model. A 3-dimensional viewing component displays assemblies including the welds. Welding information can be controlled and modified in a specific spreadsheet. A reporting tool allows generating welding reports in various formats.

The interface to robot systems has been implemented by means of neutral files in ISO 10.303 (STEP) format. The data exchange model reflects the complete set of generated weld data and includes assembly structure, assembly attributes, part geometry, part attributes, weld geometry, and weld parameters.

The project results have been successfully implemented as part of a process chain for the robot welding of sub-assemblies at shipyards in Japan during 1998.

Introduction

The introduction of automated welding facilities in shipyards started some years ago, shortly after robot technology became economically feasible in mass production environments. However, due to the different nature of e.g. automotive industry manufacturing processes, it became soon clear, that the common offline teach-in approach used in these areas was not suitable for manufacturing conditions found in the shipbuilding industry.

The offline programming process initially was a time consuming task, which would only prove to be cost effective if the automated production steps could be executed repeatedly for a larger number of production units.

As a result, two main lines of development have evolved over the last years:

- macro-based programming of robots

- automated generation of control information for robots

In the first case, the underlying idea is to reduce the majority of welding tasks to a well-known set of parameterized weld (sub-)processes, which can be configured by a minimal set of input data. This requires either an interactive visual inspection of the product to be welded or sophisticated weld path geometry analysis.

The second approach uses specific robot planning software tools to analyze the welding geometry on a case-by-case basis and to generate instructions tailored to the physical properties of the product and the robot equipment.

It should be noted that a mix of both above-mentioned approaches is possible.

A key issue in the application of these concepts is the definition of the weld path geometry. This geometry has to be defined interactively given the geometry of parts to be welded.

Based on the experience gained with generation of production data from full-featured product models it seemed a logical step to use this information base in this scenario. As a result an application has been developed in a project together with shipyard partners.

A Project to Implement Weld Analysis

In this project the product model based weld analysis was implemented. The usage scenario for the project assumes the following conditions:

- A complete design model exists, which can provide all geometrical and physical properties of the product (e.g. material, functional properties, type of part, etc.).
- A manufacturing structure is defined, which identifies the intermediate products for the manufacturing of the complete steel structure. This starts on the lowest level, where individual piece parts are combined to small units like "micro panels" up to the block assembly level [1].
- This data is automatically analyzed to identify all required welding connections for a certain manufacturing stage. The geometry of these welding connections is derived from the design geometry. Additionally site specific constraints or rules as well as technical requirements such as given classification conditions [2] are used to automatically define all welding parameters.
- Manual (i.e. interactive) definition of welding geometry as well as setting of welding parameters should also be possible for cases where local specific conditions shall override the general set of rules used for a certain project.
- The generated welding data (which could be seen as a "welding product model") is stored and maintained as part of the overall product model.
- A well defined data export facility allows to transfer any part of the product model information (including the welding model data) to robot planning software [3]. At this stage the data can still be considered to be neutral with respect to the type of robot system being used. The mapping to robot specific instructions and consideration of physical conditions due to the robot will occur in the robot planning software, which typically has some knowledge about the target robot system.

Weld Planning System

Based on these requirements an application (the "Weld Planning System") was developed and implemented which supports the welding analysis and planning of hull assembly structures as part of the TRIBON Product Information Model.

During the analysis stage, welded joints are extracted from the model based on the topology and geometry of the structure. After extraction, welded joints are further split into welds based on user-configurable configuration data. During this stage, weld parameters such as weld size, process, orientation etc. are determined in addition to the precise geometry of the weld trace.

After weld generation, welded joint and weld data can be interactively reviewed by using either a 3D graphics display or a tabular presentation.

Assembly-based Analysis

Weld planning is performed on a per-assembly basis. The system provides access to the assembly structure via a tree browser and navigation display (see Fig.1).

Using the browser window, the user can:

- identify the assemblies or parts to be analyzed
- inquire various properties about the assembly and all belonging parts
- view the assemblies or parts using a 3D viewer window.

The display includes a tree view and an information pane in which relevant properties of both

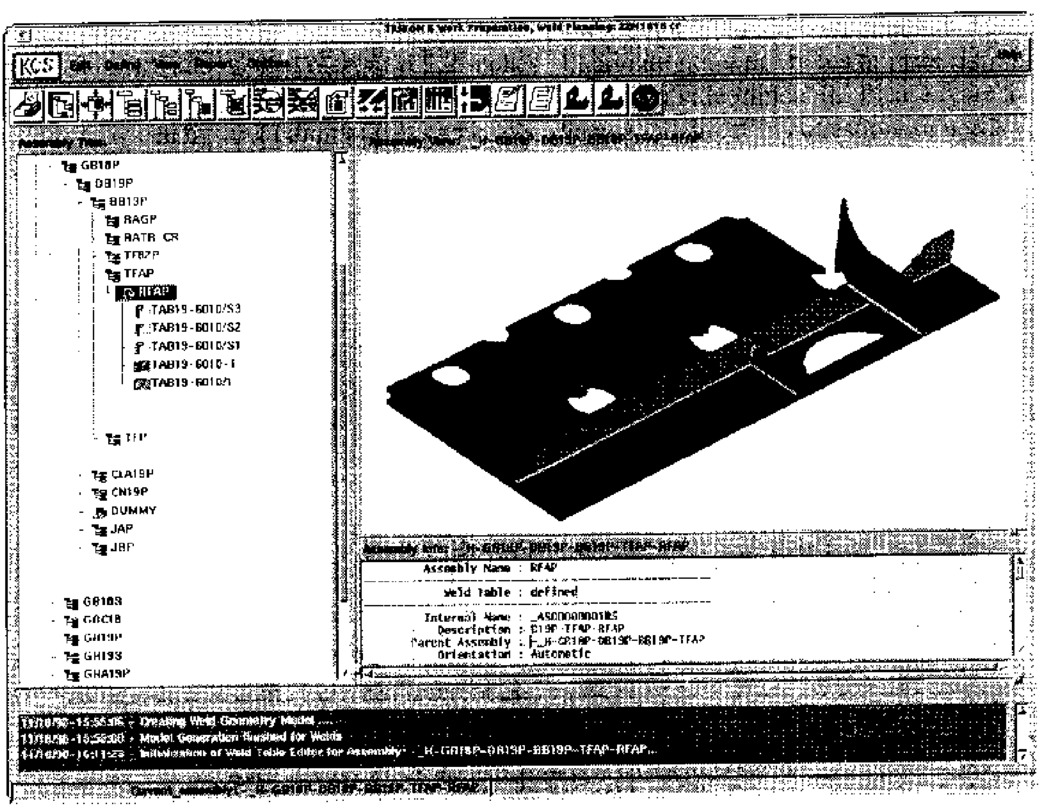

Figure 1. Tree browser for the assembly structure

assemblies and parts can be shown.

To create a graphical view of the assembly or its belonging parts a 3D viewer window can be activated. This viewer includes an interactive query facility that gives access to assembly and part information by clicking on the displayed object (Fig. 2).

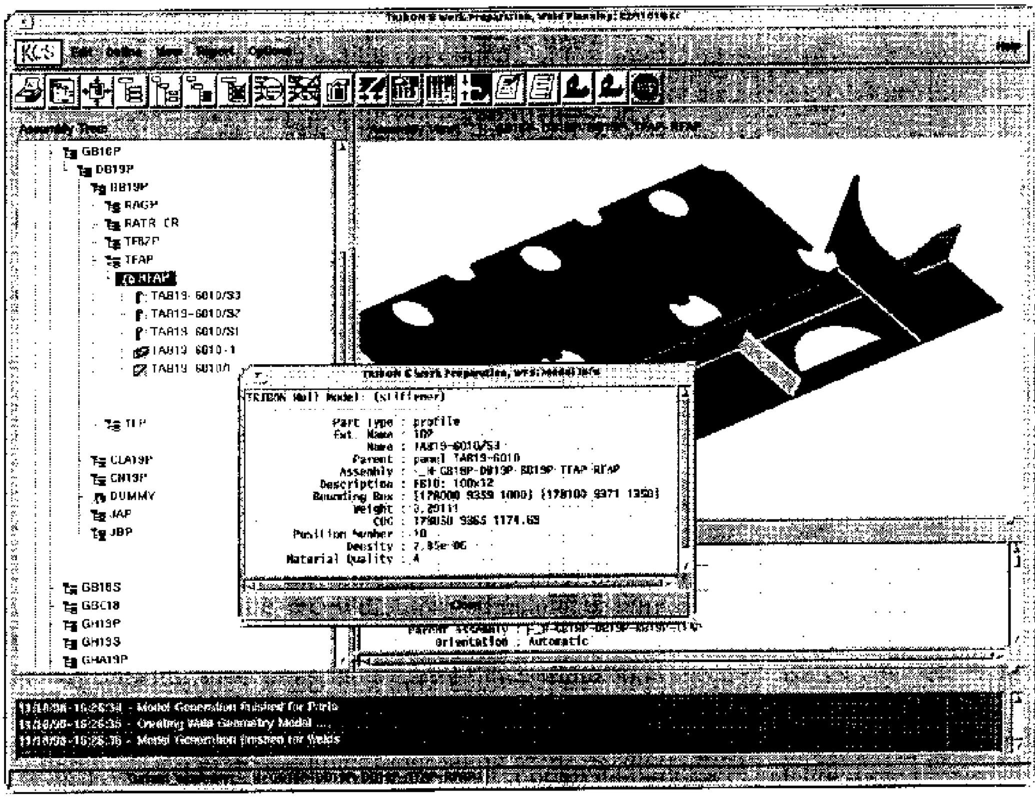

Figure 2. Interactive query of part properties

Weld Analysis

After an assembly has been selected for weld analysis, a press of a button starts the actual analysis. Identifying any possible part connection followed by a detailed topological and geometrical analysis of that specific connection performs the analysis fully automatically. As a result of that analysis a *welded joint object* is created, which represents the weld connection between two or more parts. Based on a more detailed analysis of the welded joint topology and geometry, individual welds are determined.

The following types of connections can be analysed:

- on assemblies having no sub-assemblies, a complete analysis of welds between all parts is performed,
- on assemblies having only sub-assemblies, all sub-assemblies are assumed to be completely welded and thus only welds between sub-assemblies are detected,

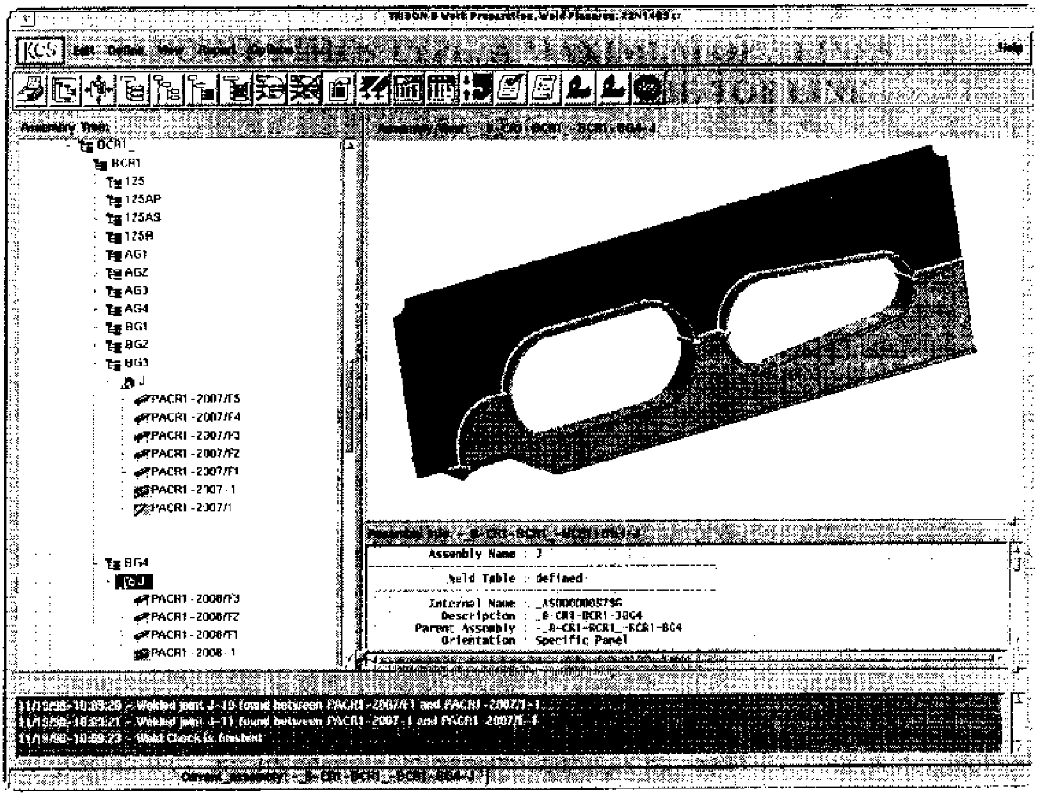

Figure 3. 3D viewing of weld information

- on assemblies having a mix of parts and sub-assemblies, sub-assemblies are assumed to be completely welded and are regarded as "parts" together with the existing parts. Thus, welded joints between sub-assemblies and parts are also detected.

The result of the analysis can be reviewed both graphically, by using the 3D viewer (Fig. 3, Fig. 4, Fig. 5) as well as textually, by using a spreadsheet-like tabular display.

Figure 4. Weld details in the 3D viewer

The tabular display window (Fig. 6) gives the user full editing capability of the welded joint and weld parameters such as thickness (weld size, orientation, process etc.). It does of course not allow the user to change the topology, which would most likely destroy the consistency of the model.

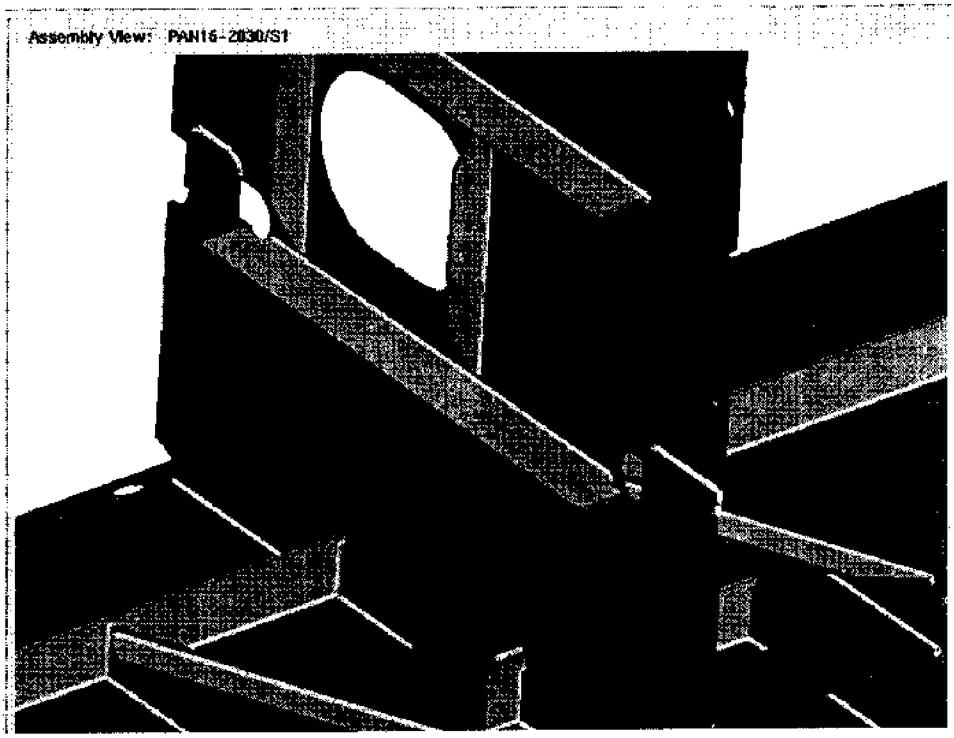

Figure 5. Viewing a complex weld model

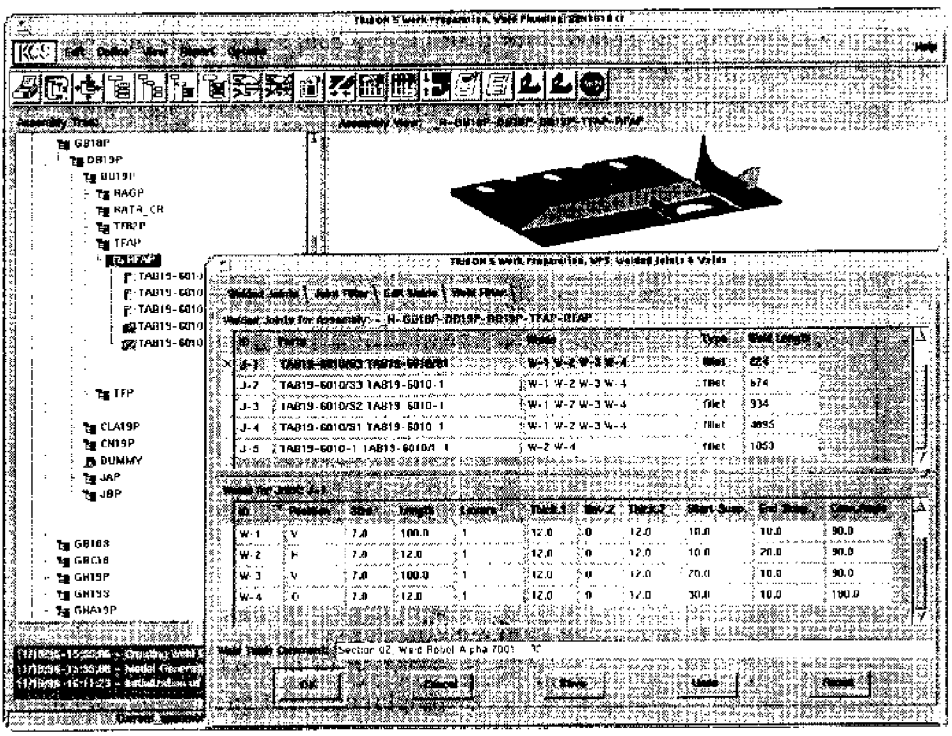

Figure 6. Tabular weld data editor

Weld Sequence Definition

Welds can further be collected into weld sequences. This is achieved by using a specific weld sequence editor (Fig. 7), which allows the user to collect, de-collect, or exchange weld elements contributing to a weld sequence. Weld sequences can also be stored in the Product Information Model and will be transferred to the robot planning system.

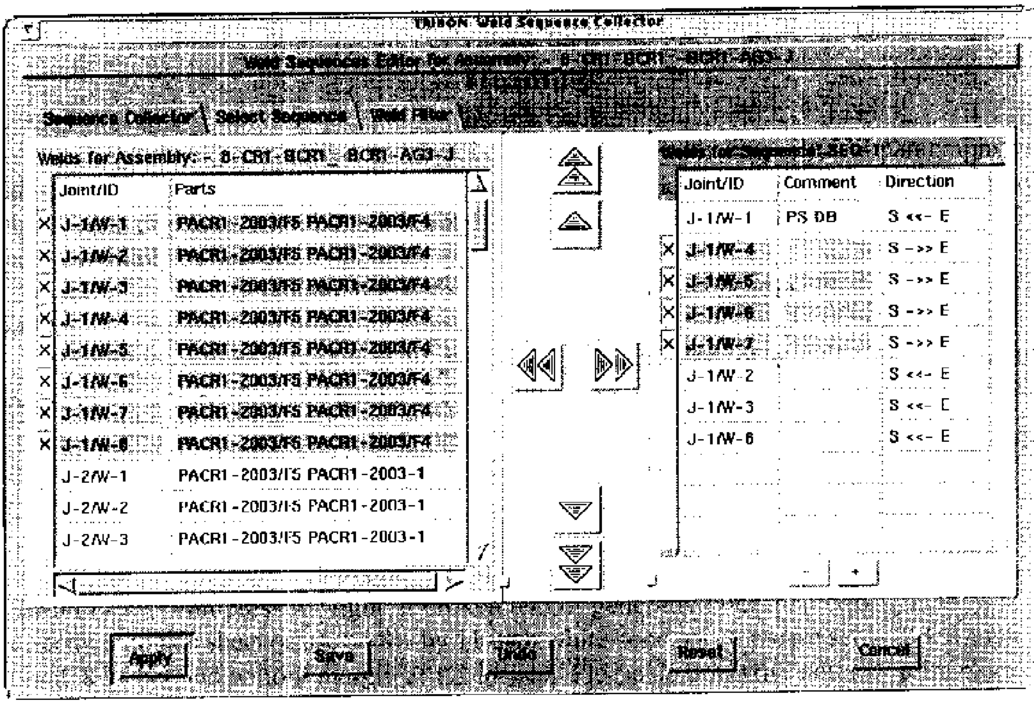

Figure 7. Weld sequence definition

Reporting

Generated data including all related product definition data can be extracted from the system using its reporting facilities which include:

- a line oriented raw (unedited) record format compatible, suitable for data transfer to any site-specific tools.
- a line oriented raw record format (CSV) which allows the data to be imported into spreadsheet and desktop database programs. (Most PC-based and UNIX-based office tools support this format.)
- formatted reports using the built-in report generator.

Data Export

Welding information and all related product definition data can be exported to neutral files using the system's Robot Interface facility.

The neutral file format is defined along the lines of ISO 10303-21 (STEP) [4]. The EXPRESS language (ISO 10303-11) [5] is used for the description of the data exchange model, which is defined close to the proposed ISO 10303-218 [6] standard for ship structures.

Assembly structure, assembly attributes, part geometry, part attributes as well as weld geometry and weld attributes are supported by the data export function.

Configuration

The weld analysis process can be configured to assign various technical parameters to the welded joints and welds detected during the topological and geometrical analysis phase. The parameter assignment can be controlled by fully user-configurable weld configuration data. This rule-sets include:

- an orientation to position mapping, specifying how the orientation of a weld shall be mapped to a predefined welding position,
- a weld size table: rules for deriving the weld size from parameters like connected part thicknesses, part type etc.
- a weld process standard table providing an optional directory of site-specific weld process including their technical parameters,
- a process selection table giving rules for automatic determination of the weld process to be used for a certain weld,

The configuration of rule sets is typically done once for a project and then applied during the production-engineering phase. In fact a user applying the analysis functions by default does not have access rights to change the rule sets.

Welding Product Model

A key concept of the Weld Planning system is the extension of the Product Information Model to also cover all welding related information.

Welding data are structured by assembly. I.e. for every analysed assembly a corresponding weld object is generated. An assembly has a number of connected parts (or subassemblies). The topology of a part connection is captured as a *welded joint*. The *welded joint* has a type (butt or fillet joint) and is composed of a number of *welds*, i.e. the actual weld traces of a joint. A *weld* has a set of geometrical and technical attributes.

The weld geometry is described by

- weld contour,
- weld size (A measure or leg length),
- weld length,
- rotation and inclination angle of the weld with respect to the manufacturing position of the assembly, and the
- connection angle of joined parts.

Technical weld parameters include

- welding position (flat, overhead, etc.),
- weld process,
- number of layers,

- test procedure.

All *welded joints* and *welds* have a unique identification in the scope of a ship.

System Architecture

The components of the Weld Planning system are shown in figure 8.

Based on product model database facilities, an *application language interpreter* serves as the application core. The term application language refers to assembly and welding specific commands that are processed by the system internally.

A key component is the *geometric engine* which is based on the ACIS geometric modeling toolkit [7] using full scale solid models to support detailed analysis of complex geometric configurations with very high precision. However, while geometric analysis is very important, the efficient analysis of welded joints only becomes possible due to a maximum exploitation of the topological and functional properties available from the Product Information Model.

The *weld analysis and modeling* component processes intersection information from the geometric engine and further calculates weld parameters based on configuration rules.

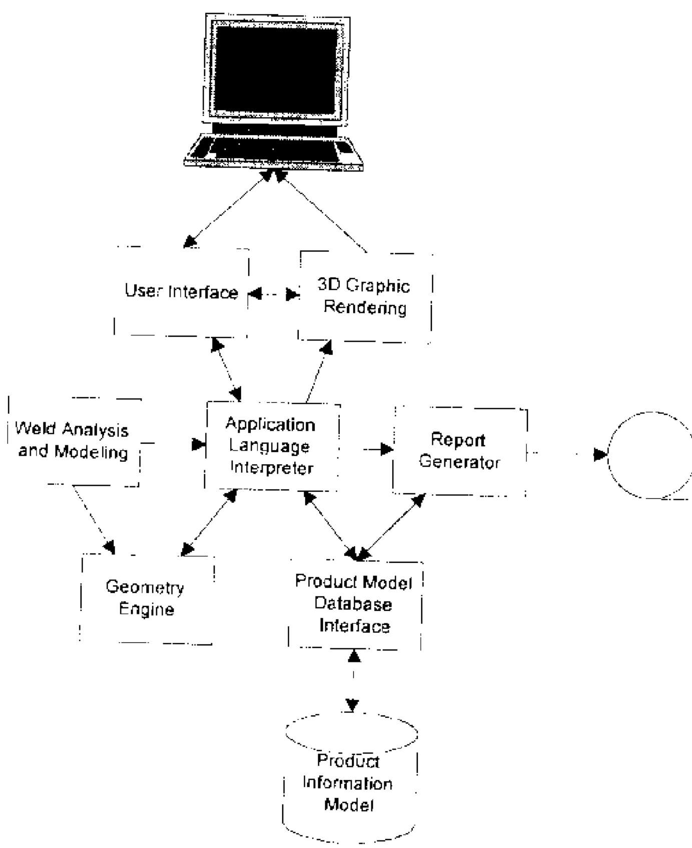

Figure 8. Weld Planning System Architecture

Summary and Outlook

The first robot line successfully started operation based on Weld Planning data in Japan in 1998. The application has also been implemented as a production engineering tool to supply input for planning purposes. Both application areas have shown the potential of the Weld Planning System.

Ongoing development is targeted towards support for more complex classification rules, e.g. taking a tank content into account when calculating the weld size.

Various production engineering tasks have been identified that can be supported by the generated weld information. Among them are:

- Work Content Calculations
  Summed up weld length, classified by weld size and process, are direct input to work content calculations and are straight forward to implement.

- Cost Estimation and Calculation
  As for work content calculation, welding cost is determined by weld length, sie and process. Implicit cost, e.g. for fitting, can be derived from the available information of the complexity of the welded joint and the positions.

- Production Planning
  The planning and control of welding operations can be based directly on weld planning data.

- Job Descriptions
  Weld reports can be attached or included in production drawings in order to automate the generation of welding job descriptions.

- Quality Control
  Welding quality control, e.g. for offshore projects, requires unique identification and storing of all welds. This is accomplished by the integration of welding information into the Product Information Model. Test procedures can be defined for welds. Welding reports are available for quality control activities, surveying and for the import into corresponding software systems.

A significant part of these tasks is performed manually today. Weld Planning provides powerful concepts to reduce effort and cost and at the same time improve the accuracy and quality of welding related calculations and activities.

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AUTOMATIC ROBOT PROGRAMMING FOR WELDING OF SHIP STRUCTURES: WELD DATA GENERATION AND USAGE FOR COLLISION FREE ROBOT PATHS.

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Abstract

This paper describes the software modules on which the automatic arcwelding robot programming is based at Fincantieri Shipyard.

The first module is used to compute and extract the weld information connected to each assembly phase where robots are involved; this software is integrated into Fincantieri NuovoScafo, a multi-user object oriented system for ship structure design. Welds connecting metal pieces are available within NuovoScafo: a module has been developed to consider the different assembly phases and evaluate only those welds involved in that phase; if necessary, welds are split according to the manufacturing needs.

A second module - developed on top of a graphic simulator: an arcwelding robot instruction program - allows importing the weld information generated, and process the workcell just created. Within the robot instruction program, the already available graphic simulator language has been integrated with the arc welding macro programming feature; also weld information interface and workcell scanning for automatic execution of user developed macros have been created.

Introduction

Constant cycle time, standard quality and efficient work schedule added to global cost reduction. These are the main goals to reach while introducing automation into industrial processes.

And, in the recent years, automation of processes has been one of the aims at Fincantieri (Italian Shipbuilding company that design and build big cruise and merchant ships as well as high-speed ferries and navy vessels) to pursue the tradition of innovation and research and development in the design and shipbuild activities.

To make evident the advantages linked to the automation of processes, this paper will outline the development of shipbuilding process of our ships till the current level of automation.

Until few years ago, the design phase of our ships was based on a cad system that have been developed within Fincantieri in the 70s. The system was based on few initial core modules; then, considering the increasing needs of information, other modules have been added. Big drawback of final configuration was the low level of global integration between the programs and the number of reinput needed in the different steps of design process.

The shopfloor typically had no information technology and only paper draw documents were available. The introduction of numerical control machinery involved new needs and blue collars became familiar with tapes and floppy disks. So the design office had to be equipped with new tools to support the arising needs and therefore the creation of the software modules above mentioned.

The first step of real automation started in 1994: the FASP project (Flexible Automation in Ship Production) introduced into the Fincantieri shipyards robots for cutting, assembling and welding, area controllers and scheduling systems.

These innovations led to a reduction of workers. At the same time all the design offices have been equipped with new software systems to face the continuously increasing need of electronic information required from the workshop.

In parallel to the starting of the project for the automation of yards, NuovoScafo have been started: a project for a completely new cad system for hull structure design of Fincantieri ships. NuovoScafo was intended to satisfy the increasing need of integration and free flow of design data among the different design steps not only within offices but also into the yards until the area controllers, the robots and numeric controlled machinery.

Automatic Robot Programming

Starting Point

Initially, robot instruction was based on an interactive graphic simulating software. On top of this standard software specific tools have been developed to speed up the process of robots instruction; in this way the global time need for the off-line programming was reduced and made equal or even less than the welding time and so acceptable.

The introduction of this software and in particular the specific developed tools made workers play a less important role in the robot instruction. In fact, duties where reduced to play with the computer and teach robots on which parts has to be welded together, workpiece positioning, run simulations to check the programs just generated and where necessary make corrections.

Interactive programming based on graphic simulator and primitives

The majority of welds used for ship construction can be categorized into families (one family groups welds that connect objects with similar geometry). Each family can be programmed as a "primitive" or template, then parametrically mapped to each weld seam. In this way, programming curved blocks - with highly individual and curved seams - for example, is as easy as programming flat blocks having mainly flat and similar sections.

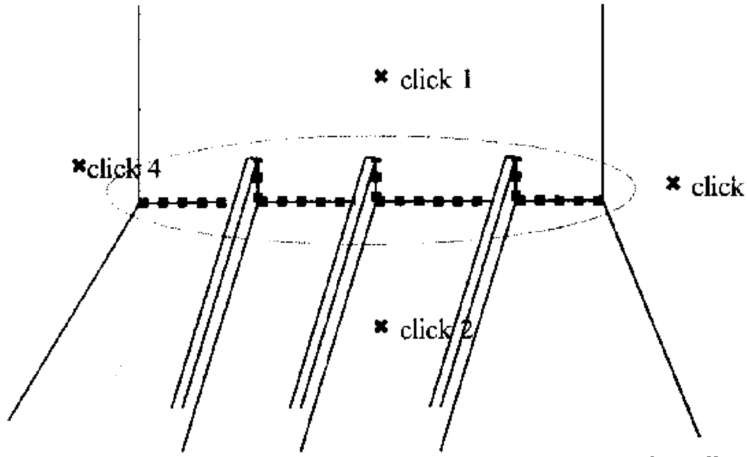
The primitive capture years of welding experience and form a knowledge base for preserving vital information.

User defined parameter values are used to define tag locations, orientations and auxiliary data. This allows one to limit the number of interactions by the user and perform rapid selection of weld zones that have similar, but not identical, geometry as is commonly found in ship structures.

A parameter popup is used to define the location and orientation, with respect to part geometry, of individual tag points. It is also used to define starting and ending conditions (i.e. distance, surface, vertex, etc.).

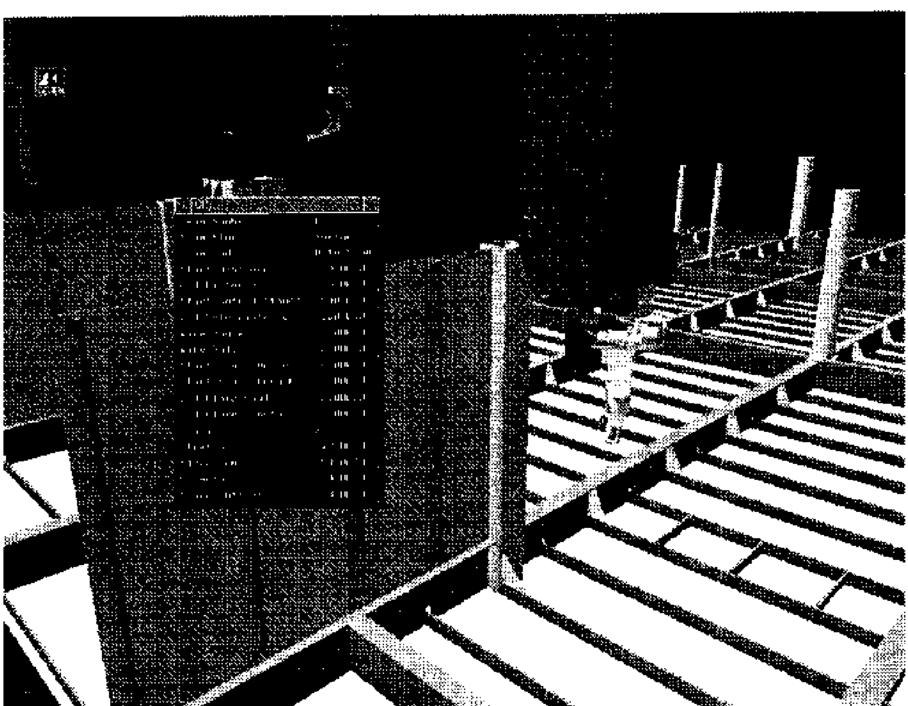
This popup is generated by what are referred as primitive files. Primitive files consist of system variables and keywords that define how and where to generate weld paths.

Primitive file contain variables used to define the location and orientation of tag points in and around a joint or combination of joints.



Only few mouse clicks on "most meaningful surfaces"

Libraries of primitive files have been created to define standard, or unique, joint configurations. Keywords are available to prevent the simulation system operator from modifying primitive system variable values. This helps ensure that important system variable values, that are defined by weld engineer, cannot be modified during primitive execution.



A parameter popup is used to define tags locations, orientations and auxiliary data.
A primitive file can be invoked using standard buttons of the simulation environment.

Once invoked, user-defined prompts contained into the primitive file can be used to indicate the type of geometry selections required to define the weld joint(s).

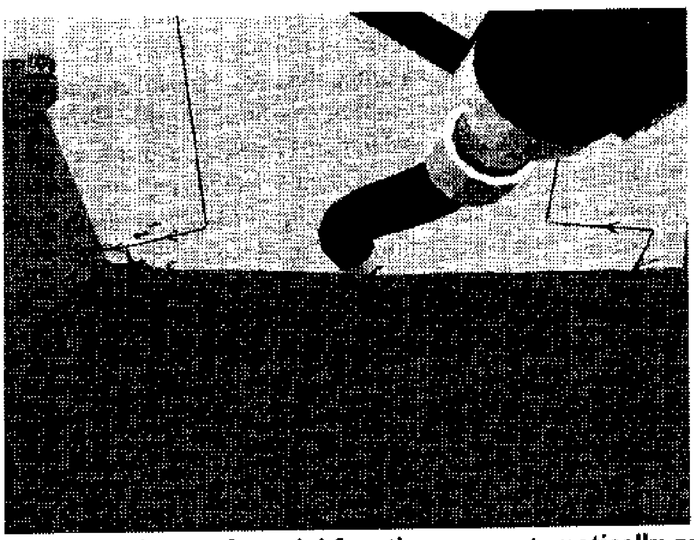
A set of functions are available to define robot specific weld process parameters including those parameters that allow the control of sensors like camera and arc seam sensing.

It is also possible to reference external weld process data files. This process data file must exist in the process library and must be loaded into the robot welding device. Table references will be automatically placed in the appropriate tag points. When the appropriate function is invoked, a robot program is automatically generated with the appropriate weld data references.

The majority of robot programming is done by users that are not computer or robot experts Therefore, it is essential that the system is easy to use and smart enough to maintain important weld procedural information defined by weld engineers.

This is why primitive libraries are created before the programming is done. In this way robot and weld engineers can identify typical weld zones and structures and study appropriate primitives. One of these primitives is able to place weld paths with more that 50 points in just few mouse clicks.

The end-user of the off-line system is not requested to examine these single points. The end-user have to consider just the seam, and decide which seam configuration is better for a given geometry. Via points (additional positions, with no particular functions, in the robot program) to ensure collision free-motion between weld joints are automatically generated. To minimize robot cycle times, weld paths are logically ordered and sequenced. Complex camera sensors and robot master-slave configurations are also inserted by the primitive without any input required from the end user.



Via points, weld points and special functions are automatically generated

In addition to automatic path generation, a mechanism able to detect errors and correct them is available to the weld and robot engineer that is developing primitives.

Primitive and interactions

Using the interactive programming system based on primitives, the number of user interactions is reduced to few mouse clicks. To program a certain typical area of the workpiece, the user only needs to execute the correct primitive and select the weld zone with few mouse click on "most meaningful" surfaces.

Reduction of the user interactions means that the system is executing automatically most of the operations and therefore errors due to wrong user input decrease.

For this reason primitives make off-line generated robot programs more reliable.

Primitive and weld process data

A set of functions and variables are available to define robot specific weld process parameters including those parameters that allow the control of sensors like camera and arc seam sensing.

It is also possible to reference external Weld Process data files. This process data file must exist in the process library and must be loaded into the robot welding Device. Table references will automatically be placed in the appropriate Tag Points. When appropriate function is invoked, a robot program is automatically generated with the appropriate WeldData references.

Automatic generation of robot programs

Today, the goal of further reducing the role of man into the process of arcwelding robots offline-programming – shortening the times needed and increasing the quality – has been reached.

A new off-line automatic programming system should let man playing an always less important role. Workers only have to recognize, in front of a computer, a wokpiece as member of geometry categories and run the process; at the end it is only required to check the log to verify that robot programs have been generated with no errors.

This new development has been started after a deep analysis of tools available at the moment: the goal was to detect possible areas of improvement without rewrite the entire system. A new need was to establish a solid connection with the design system, to allow and easy flow of data from NuovoScafo; another was to shorten as much as possible the global time needed for the development of robot programs and at the same time increase and make constant the quality of the result. Thinking at this new system it was a must keep as much as possible of the know how stored into the weld primitives: in fact that know how is the result of a great number of tests carried out "on the field".

Consequently to the detailed analysis carried out, the following goals have been identified:

1) Reduction of user interactions.

With the previous technique of weld primitives, the user had to select the different pieces to be welded together. For each weld it was necessary to choose a primitive that best fit the geometry involved, click on the two parts to be welded, select some "most meaningful" surfaces as required from the primitive, perform tests and where necessary make corrections.
With this process some problems could arise:

- the user forgets some welds; at the end the robot program is generated without any apparent error; in the shopfloor robots will weld everything except what the user forgotten to consider;
- the user puts a wrong interpretation on the geometry and chooses a wrong primitive that does not fit that topology: after that robot paths have been created by that "wrong primitive", only with great effort the operator will be able to adjust the robot positions – to avoid collisions, to guarantee

reachability, to make joint values not exceed limits - ; as a result the time spent will significantly increase;

- time spent to select geometry pieces, choose the correct primitive, perform checks and modifications depends very much on the user skill.

The solution found avoids any manual input: no more mouse click on most meaningful surfaces. The new system gets the input from the data that flow directly from NuovoScafo. In fact, each weld that comes from NuovoScafo stores the information necessary to run the old primitives to generate robot paths; in addition, greater precision and accuracy are guaranteed since weld information are automatically generated within the design system and then processed by a software procedure that will never forget to consider a single item.

2) Time as a constant

It is clear that, when primitives get the input from an interface with design system, the "human factor" is not a variable of the robot programming process. In this way programming time not only will be reduced, but also will be made constant and not variable with the worker's humor and skill: in fact programming time will be produced by a procedure that automatically consider the welds and generate robot paths. In other words it can be evaluated in advance for a better scheduling of activities.

3) Increasing of quality

Although robot programs are generated into a simulation environment where it is possible to perform a complete test of robot movements and operations, sometimes errors appear when the robot performs the real welding.

The new system will have to perform an automatic test on the robot paths just generated and, if any error or problem is detected, will make corrections. Specific developed algorithms (called methods) will have to test each robot position and, in case of errors, try different robot configurations, different external axes values, different torch orientations and positions so that the robot program at the end results free of errors. Only if none of the algorithms is able to correct the situation, the system will decide to skip that particular weld: this will be reported and the user may try to perform a manual programming with "classic tools" or give up and make the shop workers do the job by hand.

4) Increase reliability

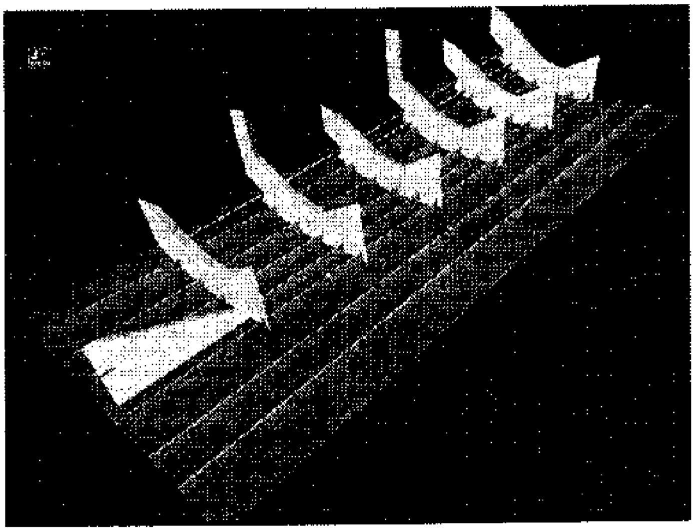
After the automatic generation of robot paths the system performs a check of each robot position and in case of problems tries to adjust them: all these operations are reported, and at the end the operator will have a complete picture of the process to get the robot program generated. In particular, errors that cannot be solved will be highlighted and the "coordinates" reported. In this way each robot program will report its history and imperfections or "forgotten welds" will no more pass unnoted.

To sum up, reaching these goals means getting the following advantages:

1. Input is performed automatically since data come from design system;
2. The complete set of welds is considered: an automatic procedure will never forget to consider one of them;
3. Algorithms for adjustment of particular robot positions will guarantee no more wrong programs;
4. A final simulation to test the programs will be automatically performed.

Interface

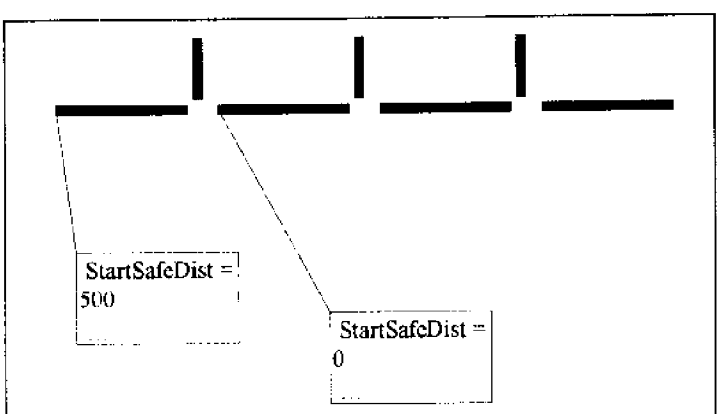
The new system has an interface to receive the geometry of the workpiece that comes from the design system, and all the data connected with welds. This interface reads a "neutral file" specially developed. Weld data is stored in the simulation environment as attribute of the geometry.



Neutral file

Neutral file is an ASCII free format file in which each geometry component is described. 3D spatial location, orientation and features of each object are described. Each field starts with a keyword that tells the object type (i.e. bracket, stiffener, pillar, shellplate) and ends with semicolon. In addition to the geometry data also a link to the production bill of materials is stored: this allows to recreate aggregations of simple objects.

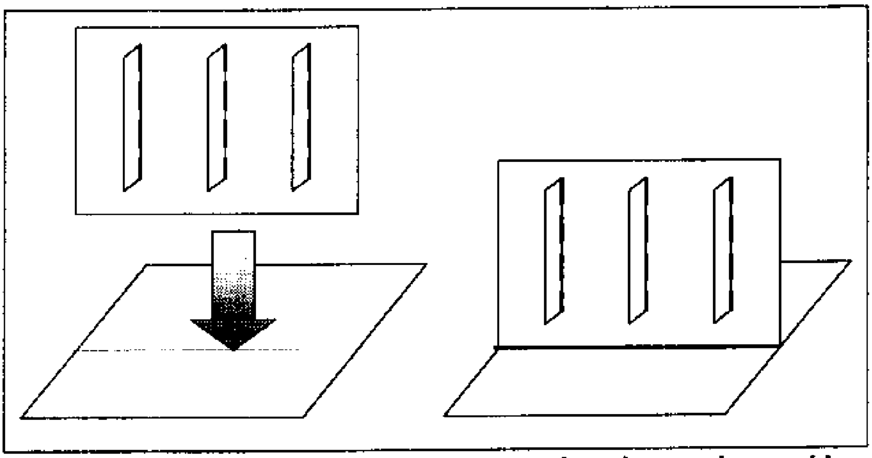
A special object within the neutral file has been designed to store weld data. Each weld will have one weld-object in the neutral file. Weld-objects store the position, start and end, information about the two elements to be welded, and a certain number of variables with their respective values. These variables are those known to the primitives and are meaningful only if the value is different from the default value established by primitives.



Weld objects may store also "primitive variables"

The aim is to store weld-objects into the neutral file to replace the manual input of the old primitives.

If welds are connecting metal pieces that are assembled objects, it is clear that only those welds to be done during the current phase have to be present into the neutral file.



Only those welds to be done during the current phase have to be considered.

Incomplete Data

Even if it is supposed that a complete set of geometry and weld data come from the design system into the simulation environment, the possibility to add data and make modifications is still open. The risk of errors is always present, and incomplete or wrong data should not be enough to stop the robot programming process.

The user will always be in the position to complete his task. All the data information relate to workpieces and welds is stored and organized so that at least using the core functionality of the standard simulation environment editing, adding, deleting are always possible.

Recognizing Geometry

After geometry and weld data are available within the simulation environment the user has to perform a key operation. He must recognize the geometry belong to a specific category of a list of possibility. Like in the previous system, primitives are referred to specific classes of geometry since the algorithms of the primitives start from geometric considerations.

The user will have to run selection rules (each primitive has its own selection rule) to define sets of welds and link them with one primitive (one primitive for each set of welds). These rules require to select few surfaces to create subsets of workpiece geometry: welds contained in that portion of geometry are grouped in one set, related to a specific primitive and completed with all necessary information needed for the automatic generation of robot paths.

Workcell Scan

At this point the user starts the generation of weld paths. During this step the robot program is created. The system scans the entire workcell. For each weld the connected primitive is executed; the robot path generated is being tested; each robot position is analyzed to make sure that robot can reach that position without collisions or joint limits problems. In case anything goes wrong the algorithms for automatic adjustment (methods) are activated.

Methods

During primitive execution, "methods" detect collisions, near miss and joint limits. Specific "rules" inserted into the primitive file tell the system how to behave to modify tag points in order to correct the error situation.

In this way test and modification become activities that are executed automatically by the system. Users do not have to take care of these tests and modification any more.

Global integration

The experience after the introduction of automation in our shipyards tells that difficulties do not lie on making "each single automated area work". The real problem instead consist in the global integration: making all the areas work together. Robots alone do not represent a big problem; instead big trouble arise when data from designers do not match what is being built in the shopfloor, when robot programs does not fit the workpiece or are not synchronized with the production schedule.

Therefore it seems that more than technical problems the real barrier to automation on a large scale is the organization. In fact organization depends on and reflects the major feature of ship design process that is continuously developed and reviewed.

The solution, that we consider necessary, is based on global integration of systems: ship design system have to be connected to shopfloor, so that each review, further development, or change can have an immediate effect on the production. Also it is evident that CAD systems based on several software modules are not able to share design data and are incompatible with such needs.

Nuovo Scafo

The design system

NuovoScafo (NS) has been studied to take advantage of the new opportunities offered by current technologies and then produce a flexible software to better meet the needs arising from increasingly complex ships, shorter production cycles and larger number of robotized activities in the shipyard.

The system supports the design process starting from the functional phase up to the workshop documentation production to assure a competitive advantage to the company in which it has been introduced.

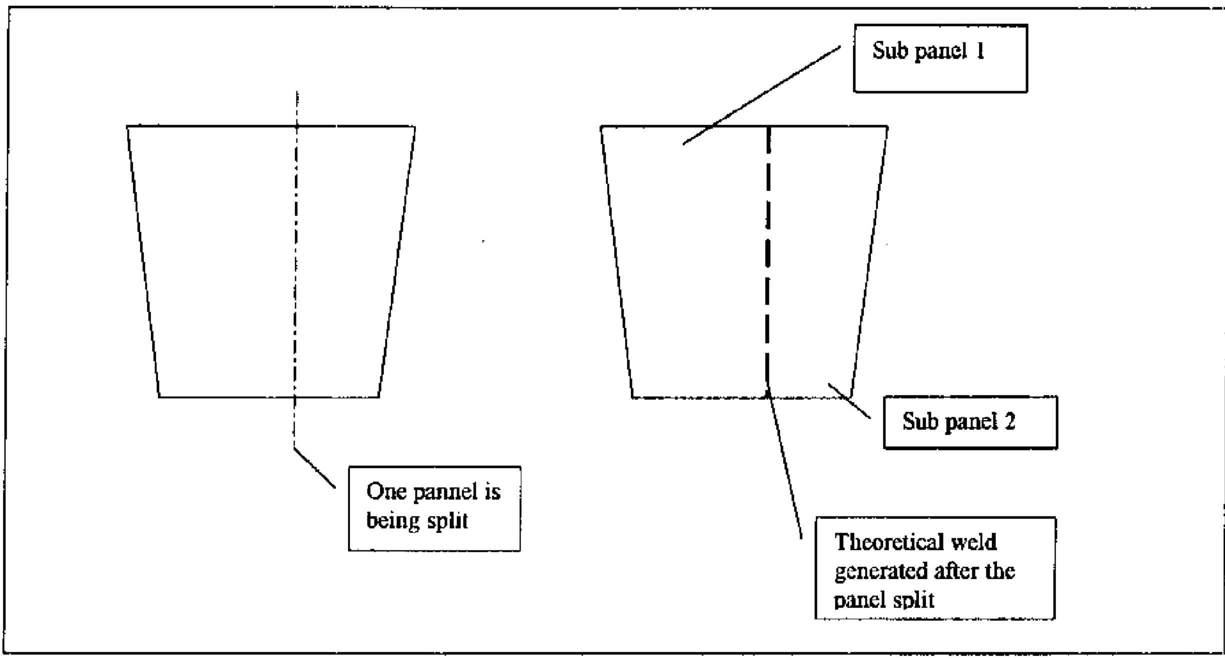
With reference to the past it is intended to assure greater design quality, shorter development cycles and quicker response to faster evolving product demands.

It allows managing of design data assuring consistency and exchange between different users, it also supports concurrent activities.

Within the NS, Design Bill of Materials is linked (BOM aggregation of objects present in the relatively static model build during the design process) to the construction bill of materials (CBOM monitors any changes to the scheduling activities and can activate the production of the required documents) to integrate design with production environment; in fact production flows are continually adapted to actual resource availability and therefore the associated technical documents must be frequently changed to support the workshop needs.

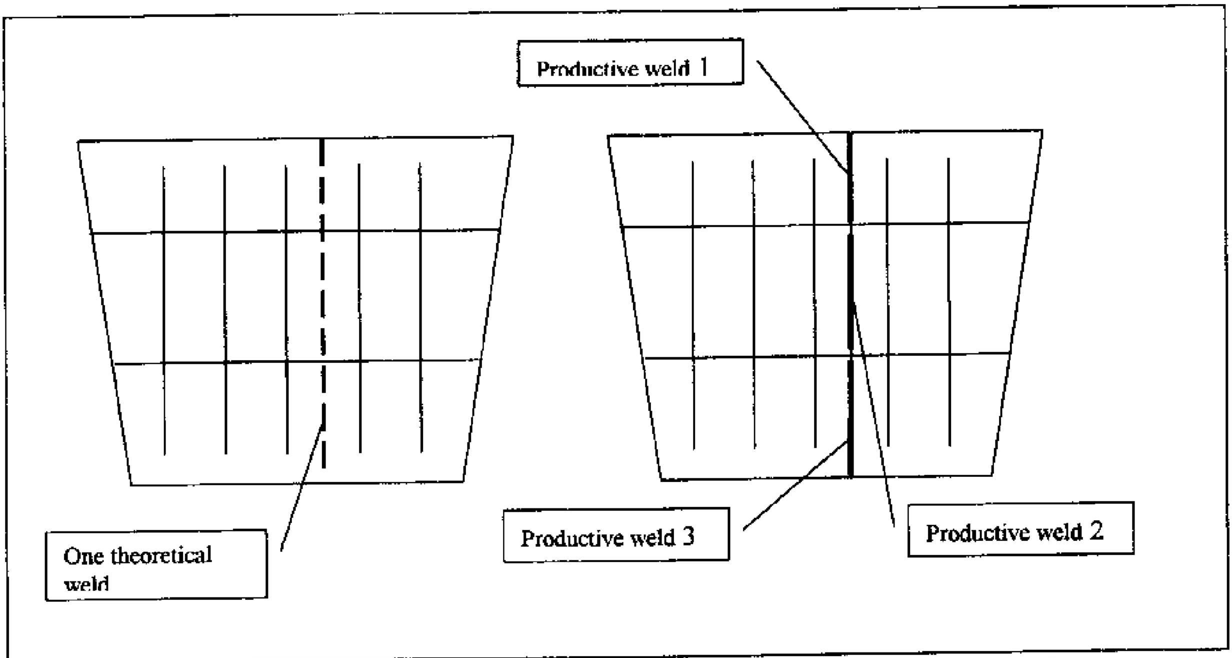
The weld-object module

The NuovoScafo kernel automatically creates weld information each time that two components are connected. For example, if the user splits a panel in two pieces, then a connecting weld is automatically generated.



Each time that a metal piece is being split, weld information are generated.

Weld defined in NS do not consider the surrounding geometry that may exist and therefore has been named as "theoretical welds". A new kind of weld has been defined to consider the entire geometry that may be important during the shopfloor production process. "Productive welds" are generated starting from "theoretical welds" and match exactly the robot (or hand made) operations; any metal piece in the surrounding area is considered to split the theoretical weld and allow accessibility of arcwelding robots. To reach this purpose a specific module has been developed.



One "theoretical weld" is split into "productive welds" according to the surrounding geometry.

Data export for the robot programming module

Within NS system each object is listed in the Bill Of Materials that is linked to the Construction Bill of Materials. CBOM has the very important goal to determine which piece is processed where; not only simple pieces but also the different level of assembled pieces.

A specially developed software module considers CBOM and the different production phase to get a list of ship components and extract their geometry data. Also, with only reference to new aggregated components of that particular production phase welds are considered; "theoretical welds" are converted to "production welds" and inserted into the neutral file.

Conclusion

The level of integration that has been reached, added to the automatism of the program generation process, proved to be extremely valid. Following these good results, Fincantieri think to continue to pursue the tradition of innovation and research. After the development of tools for a fast and automatic generation of shopfloor data starting from design model (which means that a unidirectional link between design and production has been established), the new challenge may consist in creating a feedback from the production. In this way the model might be updated to reflect the real state of ship under construction and therefore the new generation of robot programs will be able to avoid, or replace, the need of high technology sensors.

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PRE-OUTFITTING UNITS

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USING OUTFITTING UNITS BUILDING METHOD IN A SHIPYARD (UNV).

1. INTRODUCTION

Outfitting units are commonly used as a building concept, however, many different types of such elements have been presented. Actually, the outfitting unit concept that will be discussed in this paper is not related anymore with the old outfitting process, but with the whole ship's assembly procedure. That is to say that outfitting, steel and painting go hand in hand as an integrated building concept.

But experience shows that new building strategy approaches are never totally new and that. in most cases, they have been tried on previous occasions. So, shipbuilding history is a subject that should be present in all Shipyard Manager's offices, in order to avoid repetition of past errors.

In this connection, the paper will introduce the classical outfitting unit concepts and will conclude with a better adaptation to each specific case.

2. OUTFITTING HISTORY

The Market conditions are very strong in the Shipbuilding Industry, and Yards are not able to modify them. One of the most demanding conditions is the fact that every vessel must be a prototype. Only very specific cases may be considered as exemptions to such a rule: series of ships in the forties in the USA, Japanese construction of VLCC's, container ships in Holland or Germany, or small vessels like fishing vessels, tug boats, etc.

The concept of a single prototype is very painful for Yards. Many efforts have been made to compensate its negative effect on the economical result of shipbuilding.

The logical approach is to try to standardise components. Nevertheless, the Yard's standardisation of components has the negative effect of its incompatibility with the commercial availability of such components.

Additional efforts have been made to reach an agreement with the ancillary industry to get elements and components that, standardised, could be found in the normal market. In some countries, this goal has been achieved more efficiently than in others. In general, the overall result has not been a big success. The standardisation of Yards was a very costly process that, in many cases, ended in a high price range of products. The exception was the case when the Yard was able to present a sufficient amount of procurement of such a component, or when the standard coincided with one of the commercial or international standards, or when several Yards decided to co-operate in purchasing elements.

After a heavy reduction in their internal building capacity, Yards started an outsourcing that led to agreements with the ancillary industry to transfer to them the building of the units and, if possible, in a standardised manner, even if their components were not standard.

This apparent contradiction is the key to translate into a series construction what, in the market, is a single prototype.

Initially, outfitting units were defined after the engine room had been designed, by dividing the existing engine room design. No system relation was intentionally established, given the fact that units were compounded by elements with geographical grouping criteria, and without a necessary relationship between them.

But this system had several practical problems:

The module or unit designs were different from each other, depending, not only on the type and size of the vessel, but also on the selected supplier who may or might not be part of the standardisation agreement, depending on the Owner's approved equipment.

As the Yards were reducing in-house capacity, the following step was the possibility of using the outside resources to define and build outfitting units. In such a case, and contrary to the previous tendency (series fabrication in the Yard), standardised components were not a so conditioning factor for the repetition of units. The supplier was able, in the majority of the cases, to build the units with his own standard or no standard components.

But the geographical module conception was not suitable (except for pre-outfitting made on the steel blocks), because the unit design was not linked to the supplier's availability and standard module (not component) design. The design of the unit had to be based on functional criteria, gathering elements of the same system. Being supplier's delivery, the engine room design had to be, if not a consequence of the module design, an actual interrelation between this and the ship's available space. The unit distribution was related to the functionality of each system, being the starting point for the functional units.

The rigidity introduced by the functional units was overcome with the introduction of mixed criteria, where engine room general design was interconnected with the functional units provided by the suppliers. This criterion leads to the Rational Module described below.

Finally, the normal progress of building strategy led to container modules where steel, outfitting and painting were considered as a unique building concept.

3. TYPES OF UNITS

A) ***Zone related units***: units defined based on the engine room arrangement characteristics. No previous module definition is made. After the development of the CAD/CAM/CIM design, based on a single 3D model, the units are defined as geographic parts of the engine room.

- The typical basic difficulty is the fact that the connection and co-ordination with the structural steel is difficult because no reference to the ship's structure is made on time. The module definition being delayed with respect to the steel block distribution, co-ordination is very difficult. No functionality reference is made to the unit and physical limits of the ship are an important conditioning factor for each unit.
- They are a source of transportation problems because their shape is very different from each other and they are very extended in space. Some times with a lot of equipment, and just pipes in other cases. Engine room arrangement must be made, in any case, thinking of the future unit distribution, to diminish the above mentioned effects.
- They present problems with the connections between the units. In effect, the units have been defined geographically by engine room zones, and the corresponding piping, electrical and ducting

connections are not concentrated in dedicated areas. In fact, they are extended in such a way that coincidence with so many different interconnection positions, extended in all the unit boundaries, is very difficult.

- The units are not strong enough to sustain the transportation stresses and, consequently, they require an important supporting added material, with the corresponding added weight to the ship.

B) ***Functional Units***: they correspond to engine room systems and they envelop the different elements contained in such systems.

- As a consequence of that, they can be built by the majority of the equipment suppliers, with the specific basic equipment supplied by them.
- Basic and 3D designs may be co-ordinated and interference with the steel is better planned because of the earlier unit definition from the corresponding supplier.
- Geographical reference still exists. Systems are gathered in order to be able to define the functional units with the corresponding equipment close to each other.
- The functional approach allows for a better and earlier system testing, even out of the ship, based on their homogeneous conception. In this connection, the amount of work to be done in the slipway is much less.
- Interfaces between modules may be grouped in an easier way, allowing for a better and faster connection on board. Logically, such design must be clearly thought out at an early stage in order to give the instructions to the suppliers on time and to avoid errors in the module definition. In case of having standardised functional modules, the ship's design may easily be adapted to it.
- Parameterisation of the modules is possible, and reference to basic design parameters is easier. So, the unit catalogue of the Yard is very complete and it should include the calculation instructions to obtain appropriate module for each case, based on easy specification variables.

C) ***Container Units***: they are mixed geographical and functional modules. Its most conditioning design concept is the functional one in order not to lose the above mentioned advantages. Mainly, they are defined like actual containers to be incorporated into the ship (normally the engine room).

- Installation on board may be made even with actual container guides that act as a real discipline of building. Units are contained in open boxes with the necessary structure that are incorporated on board and welded to the rest of the structure. In service, maintenance and accessibility are assured by means of the open areas of the containers.
- They normally require a special consideration of the ship's structure around the containers and in the upper engine room areas. Modules are large and, therefore, an important part of the ship's self-supporting capability is reduced to give access possibilities to them.
- Slipway installations will require, most likely, supplementary supports. The upper deck will be specially reinforced. No twin decks are allowed in order to permit the units installation and, so, double decks would be a good solution to avoid weakness problems in service.

D) Container Units with the actual ship's structure incorporated.

- The amount of work is reduced because the true ship's structure is co-ordinated with the outfitting units, incorporating part of the ship's structure into them.
- They reduce the lightweight, compared with the other systems because they use the actual ship's structure as unit self-supporting structure.
- The ship's structure and the corresponding building process must be drastically changed. Advanced equipment definition is crucial. As a consequence, predefined or standardised units are to be used extensively. Standard hull forms and arrangements are also crucial. A proper CAD/CAM/CIM

System is also required to obtain the necessary dimensional exactitude and parameters (merit functions) control.

The adoption of outfitting units could have some of the following consequences:

i) The engine room will remain longer without the top deck. So, superstructure to be defined in order to be installed in a very short time.
ii) The engine room structure is different and would require, most likely, its study by Finite Element method. Vibration consequences of possible weakness must also be taken into consideration.
iii) The engine room arrangement is different and would require a careful pre-development to be carried out, where main routes as well as the main modules, accessibility, ergonomics, etc. to be defined, before entering the detailed 3D model definition.
iv) Side bunker tanks may be a good solution because they represent a buffer between the actual engine room arrangement and the actual ship's side, allowing for a better chance to repeat the arrangement in future vessels.

4. ACTUAL APPLICATIONS IN UNV:

The design process is as follows:

1. Basic Design: class approval, material definition and general arrangement of engine room.
2. Pre-development design: unit subdivision and space arrangement as per building strategy. In this step, modules, routing of pipes, ducts and cables, and interfaces between systems, modules and ship's structure, are defined.
3. 3D model for the engine room based on the 3D model for the steel.(See Figure 1, at the end of the paper).
4. Detailed workshop drawings: spools and installation drawings, with material lists and pallet material reservations in the warehouse, are defined.

The Yard is now in the process of a strong outsourcing due to the fact that many employees have been retired during recent years. So, the necessity of passing to the suppliers the building of the units is a must. Due to that, the trend today is to convert the old geographic orientation of the units to functional units with an still important geographic influence.

In fact, vessels up to 20.000 DWT have not enough space to establish totally functional units that could be oriented to its building in supplier's workshops. So, mixed geographical and functional units are present in almost all the vessels. This is the actual trend today in the majority of the Yards. The fact of having units of the container type or with the structure incorporated lies more in the particular building strategy of each case.

Some examples of the actual unit building in UNV are shown below.

If we consider the geographic type, we find many examples as that shown on Figure 2. The functional type may be represented by Figure 3 and Figure 4.

5. PARAMETERISATIONS OF UNITS

One of the most important issues when we talk about functional units is their parameterisation. It is quite clear that geographical units are very difficult to be parameterised. In fact they could also be studied on their basic design parameters.

Nevertheless, the less connected to systems the units are, the more difficult is its parameterisation, due to the fact that they are not related to homogeneous systems. So, if we want to define the element at a very early stage, we must try to get functional units as far as possible and compatible with the engine room arrangement.

Even in the case of functional units, it is not easy to define the parameters on which to base the standardised unit design. In some cases, this task is not of very difficult (cooling systems for the propulsion or energy production on board), but it is really difficult in other cases (thermal capacity for the cargo area, or chilled water units in passenger vessels). Definition problems come from the basic difficulties in defining their design criteria.

This way of defining the engine equipment will normally lead to slightly higher capacities. In case of module standardisation, the design criteria cannot be very specific and adapted to the current project, but following rather general design criteria with some over-dimensioning in order to avoid changes later on. Also, functional units are influencing the actual pipe and ducting routing in the way that the main routes are conditioned by the module position, which is rather fixed within the engine room or, even, within other spaces, like the cargo area. More pipe and ducting length may be expected from these techniques.

Nevertheless, the advanced design and the standard type of unit with the repetition effect in the workshop, within the Yard or in the supplier premises, more than compensate the increase in light weight and in the length of systems. On the other hand, these data are known from the beginning and, therefore, may be considered in the project.

Parameters on which to base the design of the main functional units are, among others:

- Main engines (ME) and auxiliary engine (AE) power, engine numbers and types: cooling systems.
- ME and AE power, number, type, and type of vessel: compressed air system.
- ME power, AE power and boilers power: thermal oil or steam.
- ME and AE power, number and type of purifiers: purifying system.
- AE number and power, main consumer's number and unitary power and automation basics: main switchboard and automation boards.
- Accommodation area and spatial features on it: air conditioning units.

It is evident that standards cannot be unique for each unit, but several of them depend on the different possibilities of propulsion, electrical power, equipment configuration, etc.

The functional units are very related to the three-dimensional areas like the engine room, and their functional percentage compared with their geographical percentage will decrease as we enter the two dimensional areas, like the accommodation.

The subcontracting of extensive areas of the accommodation is more related with geographical concept. The density of equipment is normally less than in the three-dimensional areas, and the spatial distribution is predominant.

In order to simplify the final configuration of the mixed functional and geographical modules or units, we will call them "rational modules".

6. ACTUAL UNIT HANDLING IMPLICATIONS

The double bottom areas are normally made of heavy steel plate thickness, making it difficult to find proper lifting capacity in the medium size Yards. So, the attractive idea of integrating steel and outfitting construction is quite limited if we try to build steel and outfitting together by blocks.

Nevertheless, there is the possibility of separating the steel double bottom plan from its associated outfitting above it when building strategy requires so. The FORAN System used by the Yard is an important tool to achieve this. The outfitting units may be conceptually independent from the steel blocks, or integrated with them.

The method of the separation between steel and outfitting units has, as a handicap, the problem of the dimensional co-ordination, and requires an advanced outfitting definition, at the stage of scantling process. The ship's configuration must be conceived in this manner, using the compartmentation possibilities to the benefit of the interior simplicity. This must be achieved both by way of classical compartments, in passenger vessels, and by way of using the sides of the engine room for the bunker required capacity: Plane and vertical lateral bulkheads in the ME and machinery spaces.

The outfitting on double bottom can, in this way, be contemplated as being split into several units of different sizes, whose design is based on the actual supplier's standards, their corresponding design parameters and building strategy implications. Also, the material cost is reduced when the constructive requirements are adapted to the supplier's standards and also the labour cost when the module construction can be carried out at an earlier building stage and, if possible, at the supplier's premises.

The general arrangement should be developed by focusing the build strategy.

7. THE "RIGID BOX" CONCEPT

There are also cases where the conceptual approach for the units, can provide additional benefit.

In fact, we could consider the outfitting units in the Accommodation and Machinery areas like rigid boxes whose handling and transportation inside the vessel is pre-determined.

Its application to the engine room or to the rest of the machinery spaces is easy if we keep the concept: No shape changes and no entering the modules are allowed after installation on board.

The additional building and Owner's benefit within this concept is the available space in the unit boundaries, which is quite interesting in order to reduce interference.

Container modules are rigid and introduce some additional constraints to the design that may also work in the direction of the standardisation.

8. MERIT FUNCTIONS:

Based on the available outputs provided by the FORAN System, "merit functions" are defined in order to evaluate the efficiency of the unit system. In particular, UNV uses, among others, the following:

- Length of pipe against ME/AE power and ME/AE volume.

- Length of pipe against pipe bends.
- Pipe bends different from two or, at most, three angles.
- Number of pipes with curvature in more than one plane.
- Length of welding seams, in case of container units or steel blocks.
- Percentage of straight pipe against the total pipe length.
- Length of Design Period.
- Number of standard units used.
- Labour cost due to modifications against pipe length.
- The classical quality indicators statistically treated as per ISO standards.
- Percentage of pipe installed before launching.

The first six functions are related with the required redundancy, with the routing and, specially, with the system pre-definition made in the Basic Engineering Office.

The "Rigid Box" concept, explained above, could also be applied to the system design. In fact, the extrapolation of the concept is very easy: At the end of the day, we are just introducing an additional constraint to the design, that may be physical (length of pipe or welding, pipe bends, geographical extension, etc.), or conceptual (redundancy, ergonomics, design criteria, etc.). The earlier 3D model development the better control of the merit functions.

The other merit functions are clearly related to the level of advanced definition in the 3D model versus the later equipment modifications, and the complexity of the interconnections between outfitting units. Once again, the "Rigid Box" is working in our favour: the less in situ adaptations, the less modifications.

The concept of how long important or complex areas can be kept open during the building period is introduced in order to evaluate the "confort" to work, specifically, in the machinery spaces on the double bottom. However, other areas could also be considered in this connection (complex equipment areas or outfitting units, etc.). To achieve this, the general arrangement must take it into consideration. The way in which these concepts are integrated with the conceptual General Arrangement Drawing may be considered as its "merit function", and plays an important role in the future design and building development.

In the Ferry and Cruise vessels, the solution given was to agree with the Owner the areas with less added value placed on top of the ME room, and the ample provision rooms required, on top of the AE Room. So, the completion time for both was shorter than the required time to finish the forward cabin areas where more outfitting was needed. In this way, the lower complex areas in the aft part were connected vertically to the easier ones in the accommodation. The easier areas in the double bottom were connected to the more complex ones in the accommodation. The boundary in between was fixed in the AE room, made transversally in order to achieve good damage stability behaviour. No lateral compartments were devoted to machinery or to stores, so that no permanent access through ruled ladders was required. See Figure 5.

In the case of cargo vessels, the situation is easier since the engine room will be covered with the accommodation tower, which may be prefabricated apart.

9. CONCLUSIONS

UNV introduced in its building strategy two new construction concepts:

The ship rational module:

The definition of modules must be adapted to every building strategy so that a combined geographical and functional solution is to be found focussing always on its capability to be repeated in future projects. This design process leads to a rationalisation of the units, with or without structure integrated with them. Added value building process must be developed by means of interim products that increase their value by addition of new building pallets formed by information, materials and working instructions.

The rational module is conceived as an interim product itself whose combinations give a wide range of final sub-products.

Rational modules must be very related to the supplier standard and to its building possibilities, within the general outsourcing Yard's process.

The benefits are in terms of standardisation, anticipation of the building strategy and, even, integration of the operative and safety constraints as part of the ship building process.

The rigid box strategy:

The concept of the rigid box allows for a more pre-determined building planning and process, increasing the repetition of elements and giving additional building tolerances.

Savings in Production:

The introduction of the two above mentioned concepts, together with the use of state of the art CAD-CAM-CIM System, allow for a more efficient building strategy which, mainly, leads to a competitive differential value.

Our competitiveness may be based on a reduced cost or on a reduced delivery time. Actually, in a first approach, the reduction in delivery time leads to a reduced cost and is very much appreciated by Owners.

The evaluation of design alternatives connected with the optimisation of our building methods and possibilities, is a basic tool to achieve the mentioned goal. The target is now a reduction in the delivery time of about 20% of the old one.

An important decrease in the in-house workload capacity in the Yard leads to an outsourcing process that requires an important mentality change. Most of the units (steel and outfitting and combined) will be built at the Subcontractor premises instead of the Yard itself.

Powerful CAD design tools, the use of merit functions in order to evaluate our design efficiency and the systematic repetition within a general unit standardisation process connected to the Subcontractors available equipment, are the keys to a successful shipbuilding result.

USING A SINGLE 3D MODEL SYSTEM IN THE OUTFITTING UNITS DEFINITION.

1. SINGLE PRODUCT MODEL

The design of a ship by using a CAD/CAM/CIM System is carried out by producing a soft model as close as possible to the future real ship. Modifications can be easily performed while the project is going on, improving the design and ensuring final high quality.

The FORAN System manages a single 3D model, with all the information stored in a single and multi-access database. This is a simple way to ensure that all the people working in the project are using the most up to date information of each discipline: hull structure, pipework, ductwork, electrical design, etc.

The users will be reading and using the information of the single 3D model coordinating the different disciplines in order to reach the best design.

2. DEFINITION AND MODIFICATION TOOLS

The high standard CAD/CAM/CIM Systems, such as FORAN, usually have flexible tools to define the hull structure and the elements related to outfitting (machinery, deck, accommodation, and electrical components) with a high level of accuracy. Each structure part or outfitting element has both technical and geometrical information associated with it, thus allowing its fabrication according to the production outputs.

FORAN, as one of the most advanced CAD/CAM/CIM Systems in the market, has tools that simplify most of the tasks in a ship project, from the initial to the detailed design, covering all the disciplines: forms definition, naval architecture, hull structure, machinery&outfitting, electrical design and accommodation.

Throughout this paper the terms outfitting units or modular units are used to refer to the same concept. Their use is a good example of coordination between disciplines because most of them are usually involved in the design of the ship from the very beginning. Above, different types of units have been described.

For a CAD/CAM/CIM System, no matter really the type of unit, the requirement is to have available the necessary tools to define and obtain production information of the modular units. The CAD/CAM/CIM System should be flexible enough to be used for any type of unit definition, in different stages and by different shipyards.

One of the most powerful applications of a CAD/CAM/CIM System when working with modular units is the possibility to use standard units previously defined for other ships or to adapt them to new design requirements, by changing some elements. The availability of flexible and fast copying and modifying tools is one of the aspects to be considered when selecting a CAD/CAM/CIM System.

3. ASSIGNMENT OF STRUCTURE AND OUTFITTING ELEMENTS TO UNITS

Once the definition of the 3D model has been finished, the elements can be assigned to the modular units, according to the build strategy decided by the Production Engineering Department of the shipyard., based on the previous pre-development of units.

The build strategy is decided according to production criteria. It is considered extremely important to study the build strategy of the whole ship during the preliminary stages of the design and even before the signature of the ship contract. In this way the 3D model will be constructed complying with the build strategy, studied beforehand, with the corresponding increase of effectiveness in the detail design.

The build strategy is managed by the FORAN system as follows. The user, according to the build strategy decided by the Production Engineering Department, introduces in the database a tree representing the build process stages. These stages or level of Interim Products (IP) are fully configurable by the user. Following are some examples:

- Hull structure: minor assembly, panel, sub-block, block, section, etc.

- Outfitting: fabrication spool, mounting isometric, modular unit, area, etc.

The System is absolutely flexible, allowing the users to define stages, that could be similar or different to those listed above. Each shipyard can define, at any moment, as many levels of IP as needed, according to the build strategy decided for each ship.

The build strategy and consequently the outfitting units can be the same as the one used for previous ships. The standardisation has a great influence on the time saving in the design, purchasing and production phases. If the build process is not completely standard, a previous similar one can be copied and modified, in order to match the particular characteristics of the new ship. FORAN has the tools to easily perform these modifications.

In a first step, when defining the build strategy, the different levels and IP (units) are empty. They are initially defined as generic entities. In a second step, IP are defined and stored in the database by assigning to them elements from the 3D model or IP. The on-line assignment of elements is easily made, just by selecting them on the screen with the mouse. Both structure and outfitting elements can be handled.

The final result can be seen in Figure 6, where an outfitting unit is shown.

4. COMPARING ALTERNATIVES

The build strategy (the way in which the ship will be fabricated, by using blocks, outfitting units, etc.) is decided in the shipyard by considering the fabrication cost and the availability of equipment, personnel, etc.

The advantage of using a CAD/CAM/CIM System is the simplicity of the assignment of elements to the IP, which allows the fast availability of the necessary information to evaluate the fabrication cost, by applying the evaluating criteria used in the shipyard.

The System counts the number of sub-units in each IP: fabrication pieces (spools), assembly pieces (isometrics), fittings, equipment, structure panels, structure minor-assemblies, and elementary parts involved in the fabrication and mounting of each modular unit. Some CAD/CAM/CIM Systems, such as FORAN, can automatically classify these sub-units by rules previously established, taking into account the attributes stored in the database.

These reports can be used jointly with some other technical information supplied by the CAD/CAM/CIM Systems that simplify the evaluation of the build strategy alternatives.

The above mentioned information is referred to some of the concepts that are set out below:

- Weight: the total weight of outfitting units, including both structural and outfitting elements, could be an important limitation depending on the availability of cranes or other lifting facilities in the shipyard or in some of the subcontractor shops.
- Welding length: this is an important concept, when deciding the build strategy. FORAN System gives the total length of each welding type (butt, fillet, overlapping, etc.), considering the position: downhand, vertical or overhead. The construction plan of each IP during its fabrication is defined in the build strategy and introduced in the database as one of the IP attributes.
- Bent pipes: the pipe bending adds complexity to the fabrication of outfitting units. The high standard CAD/CAM/CIM Systems, such as FORAN, have the capability to detect the existence of bends in the spools included in the outfitting units and even to count the number of spools that have bends.
- Centre of gravity: it has to be considered when handling large and heavy outfitting units.

The above mentioned information supplied by a CAD/CAM/CIM System in a very short time is a very useful tool to be used by Production and Planning Management when evaluating possible building alternatives.

5. PRODUCTION DRAWINGS

Once the definition of the outfitting units has been finished, it is necessary to obtain production drawings for the workshops.

The production drawings consist of fabrication and assembly drawings. In each case, the drawings should include clear views and details of the elements involved, labels identifying them, dimensions indicating distances between parts or referring them to ship steel structure.

The CAD/CAM/CIM Systems should allow the users to obtain drawings that show the information needed in each discipline and as well to decide how to display this information on the drawings. The Technical Department has to comply with the requirements of the Production Department. This capability and the flexibility in configurating the drawings are very important when selecting a CAD/CAM/CIM System.

The use of FORAN System, ensures that the majority of the drawings are automatically produced. Systems have powerful tools to simplify the process of generation of the other drawings. It is very important to shorten the process of obtaining information for workshops because this effectiveness redounds in the ship delivery time.

An example of an assembly drawing is shown in Figure 8, corresponding to the module shown on Figure 7.

6. MATERIAL LISTS

It is also very important, when preparing production information, both for fabrication and mounting, to clearly identify the elements needed to complete the fabrication of the IP.

Material lists should be attached to each drawing or work order. identifying the elements involved, from the elementary ones (flanges, fittings, bolts, nuts, steel parts, etc.) to the sub-units and/or pieces of equipment, at all the stages in the fabrication process.

The high standard CAD/CAM/CIM Systems are capable of automatically producing this information and offer two possibilities: to include it on the drawings or to obtain independent lists.

The lists generated should be transferred to other applications such as Material Management or Planning Systems used by other Departments of the shipyard. Customized links are usually prepared by the CAD/CAM/CIM System proprietor, for this purpose.

In particular, using a CAD-CAM-CIM System for material reservation in the shipyard stores is very interesting. In fact the production pallet may be totally defined in the Technical Office. A production pallet is a package of information, equipment elements and working instructions that adds value to an IP in order to reach the next IP which in turn is used in the next IP and so on until the final outfitting unit, no matter what its type, is reached.

7. ADVANTAGES OF USING A CAD/CAM/CIM INTEGRATED SYSTEM

1. A CAD/CAM/CIM System, such as FORAN, represents a powerful tool to increase the coordination between the hull structure and the outfitting disciplines. We would like to insist on the outstanding advantages derived from the use of a single and multi-access database, as well as a single 3D model, in which all the information, from any discipline, is available to be used during the design process.

2. The use of a CAD/CAM/CIM System, such as FORAN, due to its high accuracy, guarantees that problems are avoided in future production stages. The outfitting units should perfectly fit each other or other elements.

3. An interesting possibility is that designers can work with preliminary information, just by knowing the position of the equipment connections and their maximum sizes. Equipment can be temporarily represented by a box with these maximum dimensions.

   Once the final information is received, it is introduced in the 3D model only to check some possible discrepancies with the original dimensions or connection positions. In this case, the possible clashes would be automatically detected by the System. This is a way to save time, advancing in the development of the detail design without reducing the quality of the information for workshops.

4. A direct consequence of the use of a CAD/CAM/CIM System such as FORAN, is the easy execution of modifications. The better the System the easier the modifications can be made.

   Anyway, it is clear that the effect of design changes on shipyard production is greatly reduced, as the CAD/CAM/CIM Systems, such as FORAN, work against a soft model that can be changed right up until the moment in which the definitive drawings are issued. The automatic obtaining of drawings allows to have more time for evaluating alternatives and for introducing eventual changes.

5. The CAD/CAM/CIM Systems, such as FORAN, facilitate the standardisation in the design, due to the easy way in which previous units, or in general, previous designs can be used. The simplicity of the copying process and the management of modifications, explained in the previous point, lead to a more extended use of standards, which represent, no doubt, saving time in the design, and, what is more important, in the construction process.

6. The quality of the design is guaranteed by using high level CAD/CAM/CIM Systems such as FORAN, as they include many quality controls. Among them an on-line clash detection procedure could be highlighted as one of the most important.

Another powerful tool implemented in these high standard CAD/CAM/CIM Systems such as FORAN, is the "walk through" capability, that allows the users to carry out a "design review", really a second quality control, that could lead to finding a better design solution in some areas.

Another important point is the possibility to simulate, with the aid of the "walk through", overhaul and maintenance operations, guaranteeing the quality in the real future life of the ship.

7. The CAD/CAM/CIM Systems such as FORAN, are powerful tools to be used in the comparison of building alternatives, as they can report at an early phase, technical attributes of parameters needed to evaluate time and cost required to perform production processes.

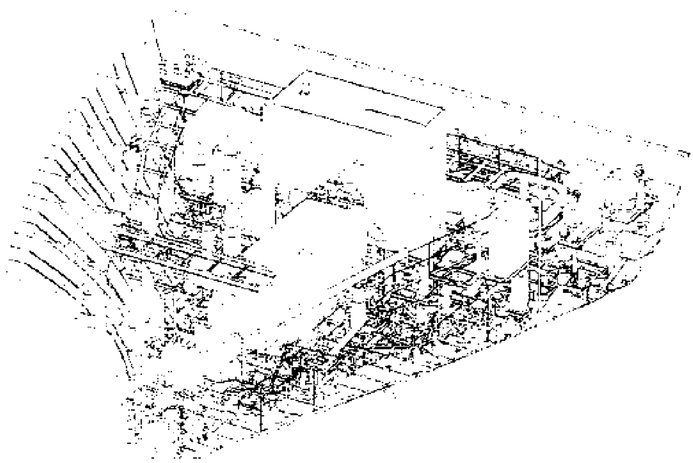
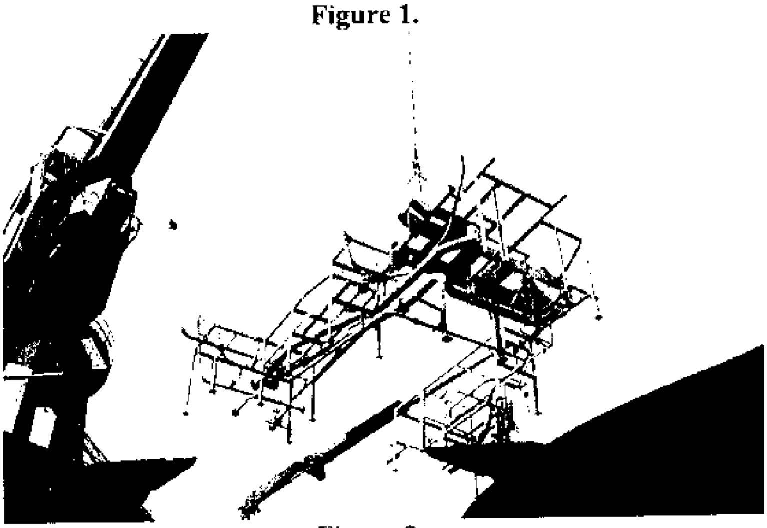


Figure 1.



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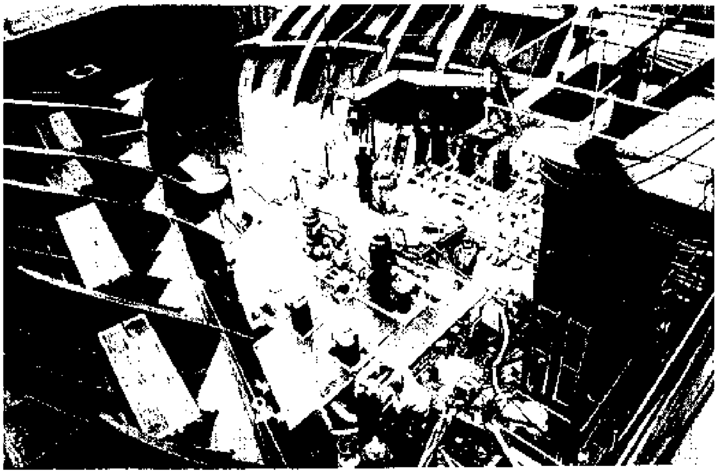
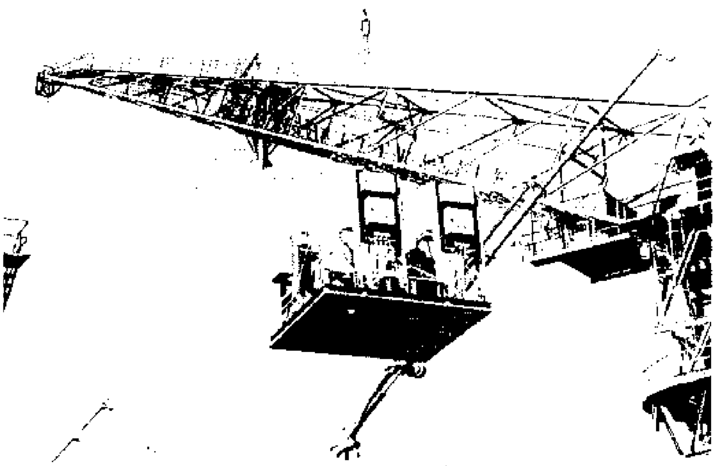


Figure 3



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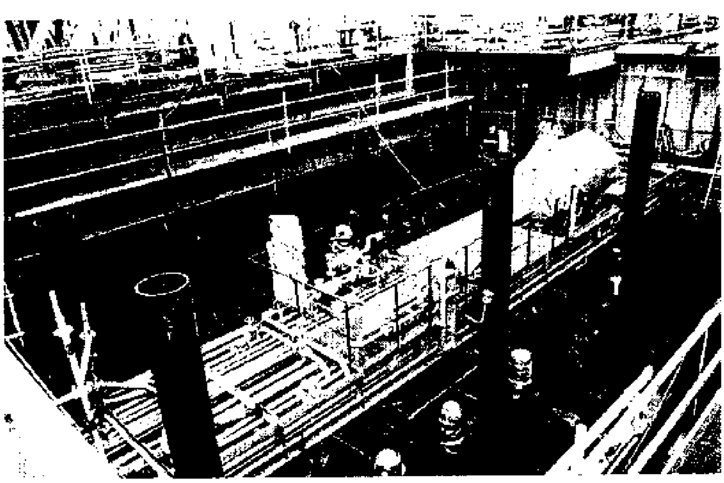

Figure 5

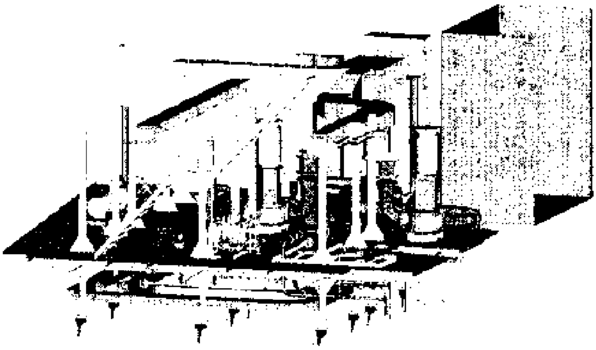

Figure 6

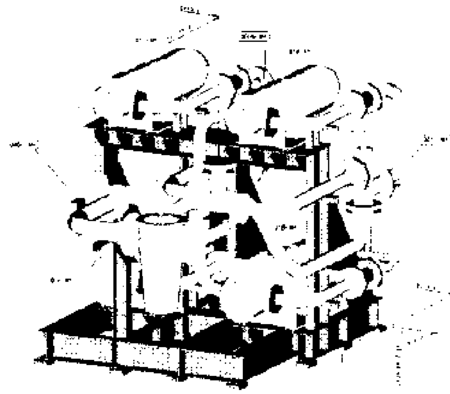

Figure 7

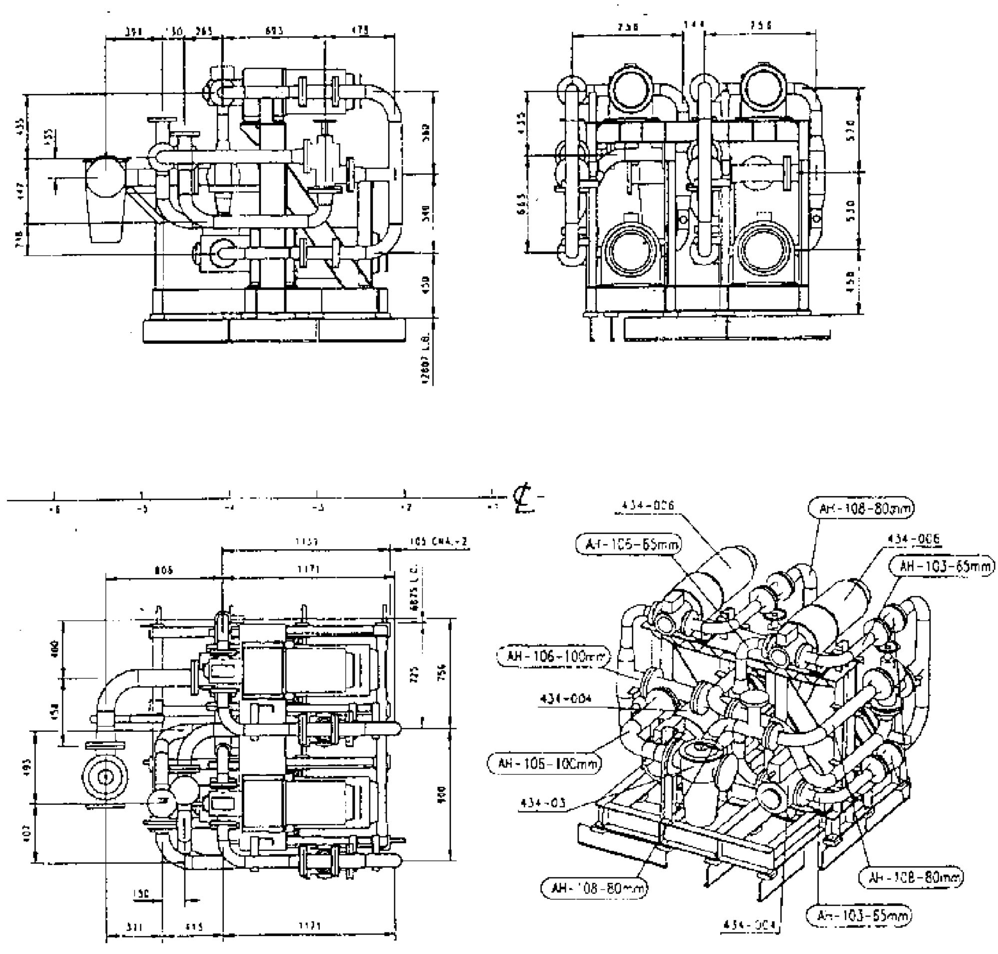

Figure 8

SHIP MANUFACTURING -
- SOME PROBLEMS OF A HULL SHAPE SIMPLIFICATION

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Introduction

Strong competition in the field of ship-building industry that has been in existence for the last few decades caused the introduction of methods aiming at increasing production output. These innovations come in different forms. One of them is to simplify the ship construction and the shape of a hull. The aim of these innovations is:

- the reduction of a labor-consuming processes, particularly those which are mechanically and automatically difficult to realize,
- modification of the hull construction by reduction of quantity and labor-consuming connecting of butt joints whilst assembling in the prefabrication phase as well as in final forming (molding) of the hull of a ship,
- rationalizing of the tolerance allowance system. The goal of this is to decrease technological allowance which avoids the necessity of taking into account variations which result from thermal processes of connecting and straightening.

The realizations of the above objectives must go back to early phases of designing ships which demands strict co-operation between design and process engineers and constructors. The study of these methods, systems and procedures are the subject of research in Poland at universities and ship building centers. This research has been financially sponsored by Research Committee in Warszawa.

The simplification of the shape of a ship's hull

This simplification is not really a new procedure. Prototypes with characteristic frame sections consisting of segments of straight lines were introduced during II World War.

The review of present solutions points to certain regular features namely:

- lengthening midship body and very often the same width of the higher parts of the hull over its whole length except for the bow-part,
- in the stern part flat wedge-like transition from midship body with shaping narrow bottom cantilever in which the propeller shaft is housed,
- forming the bow part of the ship to provide appropriate hydrodynamic properties and also equipping ship's sides with a number of flat surfaces which makes possible dividing ship shell plating into possible flat panels,
- using frame sections in which most plating surfaces are flat and cylindrical or conical in those cases where transition from midship body to stern and bow part is necessary.

Testing successive models in hydrodynamic tanks proves that simplified shape does not deteriorate propulsive efficiency or other features such as seagoing qualities or maneuverability. Usually, due to lengthening of midship body, deadweight capacity and particularly cargo spaces are increased which may be specially attractive for container loading.

The experimental project No 9 T12C 06912 analyzed two versions of bulk cargo ship of the length L =~ 190 m. [1]. A ship with traditional shape was compared to the specifically designed „simplified" version. The simplified version was obtained by modification of simplified bulk cargo ship of 65.000 tdw based on preliminary version accepted for hydrodynamic tests.

Shape transformation itself at the same main dimensions LBT caused the displacement, which was 40.831 t for the traditional version and 43.894 t for the simplified shape. Higher weight of displacement was the result of increased block coefficient and especially due to the lengthening of midship body. Table 1 presents comparison of technological features of both versions.

Table 1. Basic indexes for the shell plating of ships (L= 190 m), the traditional and simplified shapes

Data characteristic for shell plating properties	Ship with traditional shapes „T"		Ship with simplified shapes „S"		Ratio S/T
	[m.] or [pieces]	[%]	[m.] or [pieces]	[%]	
Midship body length [m.]	103	53.29	144	74.50	1.40
Relation of 3D surface to flat surface ratio [%]	-	35.00	-	25.00	0.71
Number of the steel plates used for shell plating in proposed development	471	100.00	336 **	100.00	0.71
Number of steel plates bent on rollers or conically bent	24 *	5.11	172 **	51.11	7.17
Number of steel plates with spatial (3D) bending	337	71.55	4 **	7.14	0.07
General number of bent steel plates	361	76.66	196 **	58.28	0.54
Sections of bent ship side shell plating and sections requiring prefabrication in bed	34	73.90	24 **	52.17	0.71

The maximum type-format used for the above table (according to the Polish shipyards practice) was with following dimensions: l x b = 12 000 x 3150 mm;

* - from a real project ** - calculated

The hull simplification and its influence on the manufacturing methods

The main advantage of the simplification of the shape of the hull plating is the possibility to use larger dimensions of steel plates. The actual maximum dimensions of steel plate do not exceed 12.000 x 3.150 mm in some Polish shipyards, in Germany the size of steel plate goes up to 15.000 mm and in Japan 25.000 x 4.000 mm is not unusual.

As mentioned before the main objective of the simplification of the hull's shape is the reduction of labor-consuming processes by using a larger number of flat or bent surfaces along one axis. The result can be obtained in two ways:

- in the direct way by using steel plates with one axis bending instead of steel plates with 3-dimensional bending,
- in the indirect way by modification of the shell plating.

Replacing of the distorted curvatures with straight lines or segments of a circle makes lofting easier, increasing the precision of a job and also simplifying the production patterns used in making steel plates. Bending of sheet can be carried out on the rollers and presses without the necessity of biaxial shaping which can be hand-formed.

The comparative calculation of the labor-consuming processing of steel plate forming operations was carried out for two versions of the ship „T" (traditional) and „S" (simplified), showed in table 1. Because of that calculation it was possible to prepare an evaluation of the influence of the shape simplification for bending process. The analysis showed that planned labor-consuming processing of steel plate bending for the shell plating with the „traditional" hull of the ship was equal to 3500 hours which is effectively about 0.35 % of general labor-consuming processing for the bulk cargo ship and about 0.75 % of labor-consuming processing for the hull of a ship production. The reduction of the number of steel plates with spatial bending from 337 to 24 and at the same time the increased number of steel plates with rolling or conical bending (from 24 to 172) caused the decrease of the general labor-consuming processing for the whole ship. This reduction as far as the whole ship is concerned is not of great significance.

The general decrease of the labor-consuming processes arising from the hull of a ship simplification and relating to bending processes and other operations which are influenced by steel plates shape was estimated at about 5000 men-hours which equals to about 1 % of the planned labor-consuming processing for the bending operation.

The possibility of getting indirect effects resulting from the increased flat surfaces on the shell of the ship has already been discussed. Another reason for using larger type-format of the steel plates which is part of the „traditional" ship but increases on the „simplified" ship is that the constructor and process engineer get much better conditions for projecting block dimensions. That is why overall dimensions of blocks as well as the number of plates depend on constructor's decisions. The increase of sections dimensions allows moving part of the process to the assembly room and mechanized body panels production line.

Results of these processes are as follows:

- improved butt joint quality,
- mechanized assembly of steel plates and stiffening,
- automation or welding robotics,
- decreased welding deformations.

All these lead to dimension tolerance improvement which reduces number of operations and fitting time in the final assembly of the hull of a ship.

From all the indirect affects deformations have a special meaning, they appear rather as a resultant of the welding process than the effect of assembly. Straightening aiming at elimination of these deformations causes dimensional changes in the construction. The straightening operations require a charge of heat. As a consequence there are metallurgical changes and internal stresses. Although this type of process is not the only one which causes stresses, its influence and values, beside bending are the most significant.

The increase of overall dimensions of the sections and their smaller number makes assembly easier and shortens the time of the general production of the hull of the ship. Larger dimensions of blocks allow for better integration of the hull processes with its outfitting starting with the pre-assembly phase. The decreased number of blocks makes suitable conditions for the introduction of the outfit in the early stages of shipbuilding.

Tolerance allowances

Using welding constructions in shipbuilding apart from all the advantages arising from its technology brought in grater tolerance allowances. One of the main reasons of that is difficulty in anticipating the measurement changes in prefabricated sections caused, to some extent, by assembly procedures, but above all, by shrinkage during welding. At the some time the change in technology of steel plate preparation effectively eliminated mechanical working which provided more precision, exact linear measurements as well as edge measurements. The mechanical processing has been replaced by cheaper gas cutting which increases the aberrations in straightening of steel plate edges even if all procedures adhered correctly. Connecting of sheets with adverse aberrations increases the dimensions of gap while butt jointing the adjacent panels. These dimensions usually vary along the connection.

In an attempt to overcome difficulties in anticipating exact dimensions of sections, wear margins and the range of technological allowances were expanded. However it turned out that defining and appropriate spacing of margins and tolerance allowances is a complicated problem. It results not only from overall block dimensions anticipation but also from differences in stiffeners and construction binding spacing. These problems increase when the panels are made up of curved outside shapes together with complicated internal structure.

In the research work aiming at the improvement of assembly processes and especially facilitating fitting procedures for butt jointing sections and blocks special attention was paid to:

- reducing the range of technological allowances and wear margins which requires additional cutting during the final assembly and limiting the areas of the rationally designed dimension chains,
- the reduction of tolerance allowance of the sections to the nominal dimensions taking into account the possibility of compensating shrinkage caused by welding. This can be obtained by using appropriate welding technique and assembly procedures.

The complete analysis of prefabrication processes does not exclude the possibility of cutting and fitting of blocks after finishing all these production operations, but it should only be used in case where dimensional aberrations are difficult to anticipate.

Szczecin Shipyard S.A. was one of the first Polish companies which implemented the above mentioned rules and solutions in mid-seventies, during the building of chemical cargo carriers. Improvements were required for building a large number of internal structures that were made of stainless steel or plated sheets which were difficult to be fitted and cut in the final assembly of sections. It was only possible to achieve the positive results due to detailed preparation and supervised technological processes as well as precise method of measurement.

The developed measurement technique based on methods and apparatus used in industrial geodesy allowed the introduction of a new discipline called „ship metrology" and also created a basis for measuring the accuracy of dimensions of ship constructions during all stages of technological process. The research work in this field is continued and brings new methodological and elaboration systems together with the introduction of modern measurements and apparatus.

Essential principles and rules for creating measurements allowance systems for „traditional" and „simplified" hulls are very similar and rely on:

- applying the theory of dimensional chains for the hull constructions taking into account specific properties resulting from the simplified shape,
- appropriate selection of tolerance allowances for simplified shapes and constructions,
- anticipating the dimensions of deformations of sections especially in cases where the flexibility is lower due to the lack of specific technological stiffness resulting from the spatial shape.
- suggesting methodology for defining and spacing tolerance allowances where it is necessary,
- working out automated metrological methods for „simplified" ships where it is necessary and suggesting simplified measurements or ranges of their use.

Final remarks

- Preliminary analysis of production aspects of simplifying the hull shapes encourages to continue the research work. The increased number of flat surfaces leads to the reduction of labor-consuming manufacturing processes. Particularly significant is shorter time of fitting during the assembly, and especially during butt-jointing operations. As a result sections and blocs are placed much faster, the whole building process is shorter and the use of harbor cranes reduced.
- Implementation of „simplified" shape in a particular project brings technological improvements but at the some time it must be compared with ship's exploitation effects and especially with obtaining sea keeping properties which are similar to „traditional" ships.
- The next stage after the simplification of shape, analysis of sea keeping and maneuvering properties, flexibility to local and general vibrations, should be the program aiming at modification of construction. This can be achieved by improving construction technology during the final assembly as well as by using mechanized production lines, applying automated and robotic operations, especially during welding.
- Methods and systems aiming at improving the tolerance allowance system and modernization of hull building process in the shortened assembly procedure are developed together with designing and construction work.

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A COLLABORATIVE SHOP-FLOOR PLANNING TOOL IN CONJUNCTION WITH A PRODUCT MODEL

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Abstract

Together with *Odense Steel Shipyard Ltd.*, *unique informationslogistik GmbH* has developed a 'bottom-up' shop-floor planning system which utilises product models. The combination of the planning system with a 3D product modelling tool provides all information and mechanisms needed to allow planning at the shop-floor level.

The planning system is specifically designed for non-IT-experts thus the whole planning procedure is simplified and becomes less abstract through the utilisation of the product model. The primary objective has been to create an enabling tool to allow shop floor personnel, foremen and workers, to collaborate in the planning procedure.

Introduction

Shipbuilding is a complex, complicated and multistage production process with high interdependencies. The process combines different manufacturing types at one site, from line manufacturing until construction site assembly.
The special features of customer order processing in shipbuilding lie in the individuality of the product and the required manufacturing processes together with their corresponding dependencies.

Due to the short delivery times (relative to product complexity) to be fulfilled the envisaged large-scale orders/projects require parallel production activities. This includes the simultaneity of design, procurement, operations planning, manufacturing and assembly. As a result the products are produced parallel to acquisition of product and process information. In shipbuilding, human capabilities and accumulated experience of professionals are key resources. To support the possibility of improvisation and the necessary flexibility of the employees, different production areas need maximum autonomy, also in the areas of planning and control.

These issues led *unique informationslogistik GmbH* in Bremen/Germany to develop the rough planning system GIGROS, especially designed to meet the requirements of planning of complex one-of products (Lamping, 1997). The system is, e.g., applied by Aker MTW in Wismar/Germany.

Being complex products ships are designed with the application of several types of CAD systems. Systems in use reflect the manufacturing base, e.g. steel hull, pipes , furniture etc. Common to all shipyards is the need to configure the whole ship in which the in-house designs and external supplies are integrated.(Basu, 1997). This integration process is led by constraints such as spatial -, functional -, operational and manufacturing - requirements. At the upstream end, evaluation and resolution of these constraints would need decision making tools. These decisions and the consequences hereof are the frameworks for the downstream control systems.

Promising to meet the needs mentioned above, PROMOS (**Pro**duct **Mo**delling at Odense Steel Shipyard) has been developed at OSS since 1993 and is in operation for several years now.

The mission of PROMOS has been to develop upstream decision tools and to support downstream tactical and operational processes in a continuous chain. The product model integrates different CAD systems applied at the yard and uses the data obtained for new applications in the area of decision support, production planning and production control. The system is fully object oriented and is based on an object oriented database (ITASCA).

In October 1997, at ICCAS'97 in Yokohama, the authors discussed for the first time the idea to join forces. The GIGROS system has been successfully applied in the planning department of Aker MTW. PROMOS was in operation at OSS. It was Bob Basu who had the idea for a shopfloor planning system, giving the shopfloor team members the possibility to plan their tasks autonomously within the framework defined by the OSS-planning department. The specification of tasks should be taken from the planning system (C-Plan) while the subtasks, together with estimated duration's, should be provided by PROMOS. GIGROS modules should be utilised to build an easy to use scheduler. All modules together were supposed to form the core of RAMOS - **R**esource and Activity **M**anagement on Shopfloor.

Shopfloor Planning

Nowadays, planning - systems on the shopfloor are rarely applied. In most cases companies concentrate on the control of activities, i.e. gathering feedback data. Planning is something which is done by planners in a planning - department.

Designed some time before the actual production a plan is probably outdated due to several reasons. The specific features of one - of - a- kind production outlined in the introduction of this paper sometimes cause the need for plan modifications. On the other hand such modifications have to have a certain degree. Otherwise it causes nothing but noise to change the rough-plan all the time something happens. For instance the enlargement of an activity-duration from thirty to thirty-one days in a rough-plan and the necessary redistribution of the plan is probably useless especially if the activity is not on a critical path. On the shopfloor such a fact causes the need to introduce overtime, a night shift, working on weekends etc. Thus a minor point in a rough plan has a high impact on the shopfloor were shopfloor managers and foreman have to cope with continuous changes. Resources allocations have to be changed, activities have to be postponed etc. The problem is that activities to handle such disturbances are undertaken without a solid plan behind it. For the shopfloor people it is difficult to foresee the impact of their short term decisions for the future.

Thus from our point of view it makes sense to give a limited planning-autonomy to the shopfloor in order to empower them to flexibly react on various kinds of disturbances. It is a limited autonomy because the tasks which have to be done are defined and scheduled by the planning department beforehand. Thus an autonomous planning takes place within a clearly defined framework. Within this framework shopfloor teams should be free to define and schedule the steps necessary to fulfil their tasks. Additionally it is necessary to define the sequence of activities and the interdependencies between them. Thus it would be possible to foresee the impact of changing the schedule for one activity to the schedule of the whole task. Another important issue is of course the resource allocation which also has to be done on shopfloor, having the roughly allocated hours from the rough-plan in mind.

If the idea of autonomous production areas is accepted the next step is obviously the development of a system to support this philosophy. This system has to integrate the different planning levels, i.e., the rough planning, planning of tasks and resource utilisation on a departmental level and finally the detailed scheduling and resource planning on shopfloor.

A big challenge for such a system is of course the fact that the application of computer systems is relatively new to shopfloor team members. Thus the design of the user-interface has to take into account the fact that the users are most likely not used to apply any kind of systems so far.

The following chapter will give a brief overview of the achieved results and modules as well as the ongoing RAMOS - activities.

RAMOS - Resource and Activity Management on Shopfloor

Position within Organisation and Infrastructure

Tasks to be managed in RAMOS are defined and scheduled in the C-PLAN. Each task can be divided into a sequence of steps which are provided by PROMOS. Figure 1 gives an overview of the position of RAMOS within the existing environment. The goal is to equip the shopfloor managers with a tool to support the planning on a departmental level. This includes scheduling of tasks as well as the management of resource pools. In RAMOS this part of the system is called *department management*.

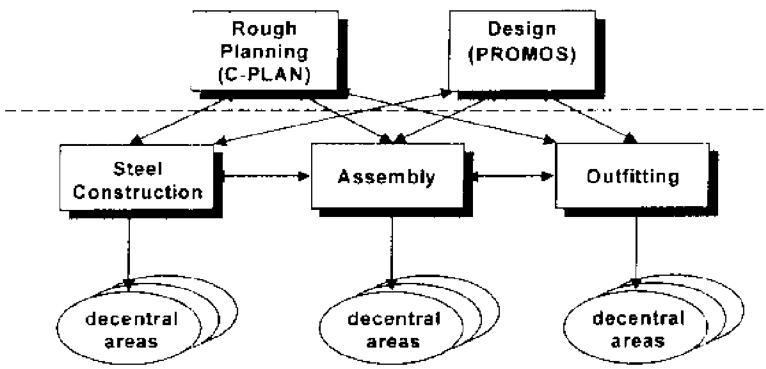

Figure 1: Organisational position of RAMOS

In *department management* the shopfloor manager gets an aggregated overview of his areas. All tasks which he is responsible for are visualised in an interactive bar-chart. For this purpose data is collected from all 'released' versions of task-plans. A stacked bar chart gives an overview of the allocated resources per trade. Thus it is relatively easy to identify critical regions. The shopfloor manager is able to manage groups of workers with the pool management tool. This tool provides several features such as the possibility to shift workers between groups for a limited time. Together with the scheduling functionality *department management* allows to harmonise the resource utilisation in a production area.

One level further down the foremen apply another RAMOS module, the so called *activity management*. The functionality of this module is briefly outlined in the remainder.

Planning Process in Activity Management

In *activity management* only a few steps are needed to derive a comprehensive schedule and resource allocation from some initial figures. The 'top-down' planning system (C-PLAN) provides the due date as well as the budget framework for the work order of assembling of a large block of a ship. Now it is up to the team to detail the work further into steps. After the identification of the steps, which can be picked from a predefined list, it is possible to detail each step further down into activities and sub-activities. This breakdown of the task into smaller entities is supported by the product model (PROMOS), visualising the details of the object to be built.

The schedule is depicted as a bar chart which contains the allocated resources in the bar for each day. Thus it is relatively easy to check the resource allocation and the schedule at the same time without having to switch between different views. The overall allocation for all categories of resources is depicted at the bottom of the screen in an extra diagram. The system was built to be applied by non-IT-experts. Thus it is possible to define most of the items graphically, including the definition of the duration or the start and the end-dates of activities as well as their sequence by directly manipulating the bars on the chart.

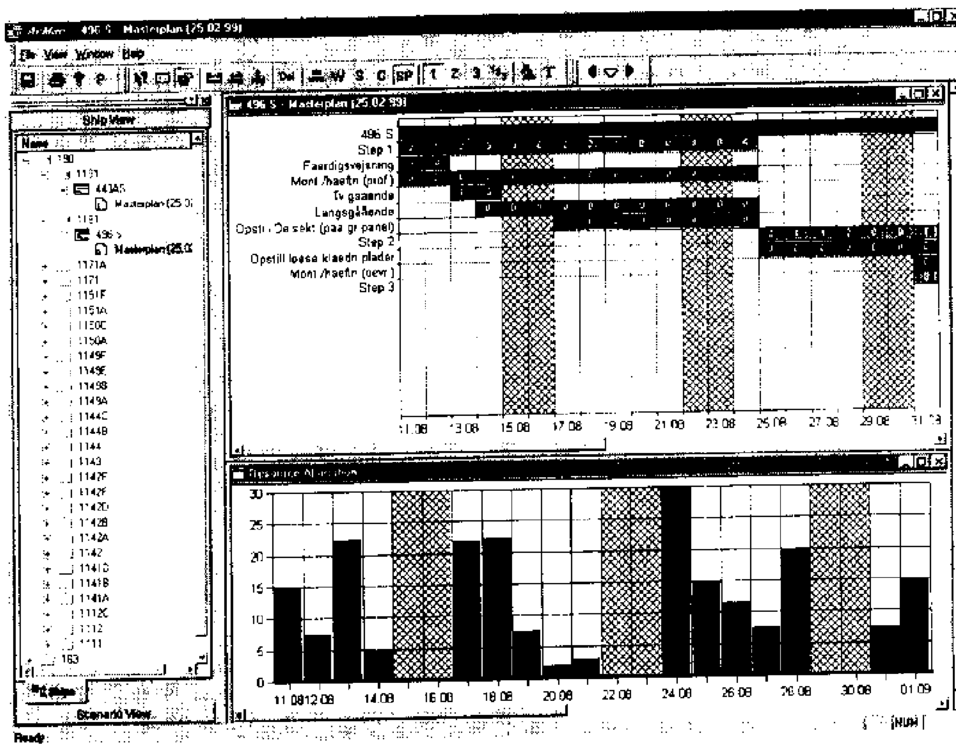

Figure 2: User interface of RAMOS module activity management

As depicted in Figure 2 activity management shows all relevant information in a comprehensive way. Steps in the Gantt - diagram are coloured green, while activities and sub-activities are blue and light-blue respectively.

In the case shown above one can see the resource allocation for a specific trade (service persons) in shift one for task '496 S'.

Figure 3 depicts the resource allocation window for an activity. The budget for the block defines the resource-availability as a whole. Now the team can allocate resources step by step while the availability gets continuously counted down. Thus the team gets some comfortable guidance and is able to progressively control utilisation of the resources. This procedure can be done for several categories of resources like shipbuilders, welders etc.

The listview on the left shows the working days according to the company calendar. In special cases it might be necessary to do some specific activities on the weekend. In RAMOS it is possible to indicate this when defining a step. A specific day can be marked to be an exceptional working day. Afterwards one can allocate resources for the activities of this step also on the day marked before.

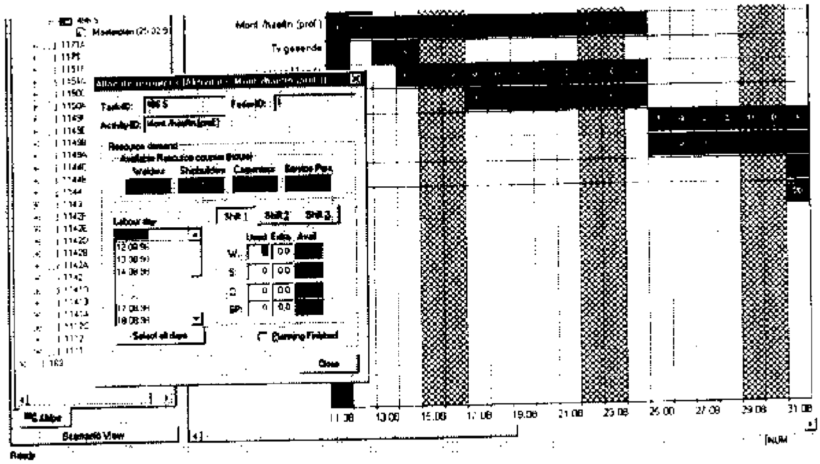

Figure 3: Resource Allocation Window

Users are allowed to define several versions of a plan. An initial version is called the Masterplan. From this plan users are allowed to derive versions. One of the existing versions of a task-plan can be marked as 'released'. The 'released' plans are those which describe the final schedule and resource allocation of a task.

Technical issues

RAMOS is built for Windows NT. As all other systems by unique informationslogistik GmbH, RAMOS was developed using Microsoft Visual C++. The graphics library was provided by Stingray, a division of Rogue Wave Software. RAMOS can store and retrieve its data from any ODBC compliant database.

Conclusion

Evaluated by shopfloor team members, RAMOS proved to be a system which is easy to use yet offering a powerful functionality. The functionality exactly meets user requirements and concentrates on those issues which are of vital interest for shopfloor management and formen. Although it is possible to use it standalone the linkage to the in-house systems, PROMOS in particular, boosts the usefulness dramatically.

The developers at *unique informationslogistik GmbH* strongly believe that RAMOS is an excellent counterpart to their system GIGROS. In combination both systems allow top down and bottom up planning in a close loop.

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