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COMMITTEE IV.2
DESIGN METHODS

COMMITTEE MANDATE

Concern for the synthesis of the overall design process for marine structures, and its integration with production, maintenance and repair. Particular attention shall be given to the roles and requirements of computer-based design and production, and to the utilization of information technology.

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KEYWORDS

Cost Modelling, Data Management, Design Tools, Fire Simulation, Hull Monitoring and Maintenance, Optimisation, Information Technology, Product Data Modelling.

CONTENTS

1. INTRODUCTION

Marine systems design synthesizes many technologies from a wide range of disciplines. Complicated demands from many aspects must be considered during the design process.

Throughout the ship design process, a representation of the ship including its structure and all components is developed and stored in ship product data models within a data management system. Following the subsequent steps in the process chain, this product data model is handed on, modified, and added to by many partners. At different stages, data is derived and transformed into multiple representations which have to be kept consistent. Every step of the design process is controlled by rules, standards and regulations which have to be observed. Disregarding these rules results in the deterioration of the product data quality with the necessity to allocate a considerable amount of resources and therefore costs for engineering change management and correction activities.

Increasing international competitive pressures are motivating all industrial corporations to continually reduce cycle time, 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 parts and materials can account for 70 or more percent of the total production costs. Re-engineering shipyard-supplier business processes can help shipyards to optimise processes and products. Overall material management and production strategies can be re-engineered and streamlined to make optimum use of in-house skills and out-sourcing resources. Thus, integrated supply chains are a key opportunity for gaining new competitive advantages and markedly improving overall production costs.

Shipbuilders face a number of strategic pressures to deliver ships in a shorter timescale, of increasing complexity and modularity, with demanding environmental rules, whilst lowering initial build and operating costs. One strategy for achieving these objectives is to keep partners more closely linked throughout the supply chain. Partnerships between customers, shipyards and sub-contractors are a common feature of naval shipbuilding and are now an emerging theme in the commercial market. The complexities of the information exchange between shipyards and sub-contractors, and the need for defined and effective workflows, including an effective engineering change management process, are crucial. The range of information to be managed includes CAD documents, manufacturing instructions, work packages, operating manuals and in-service support considerations, the creation and management of differing configurations of this information, and the compliance tracking with customer requirements.

Future ship design and production is expected to utilize an integrated set of software tools which will ultimately extend to the management of the vessel throughout its entire life cycle. A product model approach (PMA) is evolving and being developed, advocated and used throughout the industry, and it seems reasonable to expect that future vessels will be designed and built using a PMA philosophy. The first building block in this process is the generation of a central database, which will include material properties, structural component geometry, and relationships between elements. This geometric database will play a central role in future shipbuilding and marine structural design and construction processes.

Collectively many tools provide the ability to determine loads for specific operations; model and track corrosion, fatigue and collision damage and repair, produce structural analysis models for fatigue and strength assessment, and present results to the analyst to help assess risk and the most efficient maintenance actions. These tools are discussed in the framework of the design and production process in Chapter 2.

The design and construction of commercial ships and marine structures in general are characterized by small series or one-of-a-kind products which results in highly fluctuating workloads and strong competition in terms of price. Product performance and time to market requirements make it a unique engineering discipline. In order to realize new ship buildings according to the given contract specifications, dynamically changing and globally spread intra- and inter-organizational collaboration networks need to be set up and to be managed continuously. Relevance in this regard is given by the fact that depending on the ship type and shipyard business strategy, 70% or more of the shipyard's value creation is based on purchased services and equipment (Bronsart *et al.*, 2006).

In the scope of this report, the term "Information Technology" (IT) is used for methods and systems to support the exchange of product and process model data in the overall design and production process. Tools to perform specific tasks are interfaced with the help of IT methods and systems either in-house or between partners (companies) involved in the numerous ship design and production process phases. At the same time, ship owners and operators are becoming more demanding in terms of cycle time from contract to delivery, which results in shipyards becoming more reliant on a network of design subcontractors. The subcontractors are often geographically dispersed, which creates challenges in developing a fully integrated product model to support the vessel construction. Issues and challenges that are faced and to be solved in such a distributed design environment are identified and alternative approaches are described in Chapter 3.

Design for better maintenance and fewer, less costly repairs is one of the critical issues for designers. One of the responsibilities of design is to foresee the particular critical areas prone to failure in operation conditions, and to avoid such failures by appropriate design solutions at various design stages. These measures, addressed in Chapter 4, will reduce the cost of maintenance and repair during the life cycle of marine structures. Life cycle costs can be reduced by various design strategies such as the adoption of standardized structural parts, standardized module packages including prefabricated passenger and crew cabins, prefabricated pipe packages, and other integrated units. Using standardized modules not only benefits the owners owing to better reliability, less weight and space savings, but also holds advantages for shipyards by reducing design and production costs.

Optimisation is playing an increasingly important role in the design procedure for ships and offshore structures. The multi-stakeholder approach is a novel methodology for system's design involving a limited number of institutional users, producers, operators, controllers, and it is conveniently named Multi-Stakeholder Design. This is indeed typically the case for a ship design, where shipyards and ship owners need to jointly accept the final design alternatives. Major risks in the successful full-scale development of complex engineering systems arise from the challenges of effectively addressing the competing needs of improving performance, reducing costs, and enhancing safety. Strategies and approaches for optimisation of marine structures is the topic of Chapter 5.

Recent advances in design tools are addressed in Chapter 6. Of particular emphasis is the discussion of advancements in fire and smoke considerations. Fire science today, with new powerful and affordable computers, has access to an vast field of numerical simulations of fire and smoke. The fire is no more a standard temperature curve but can now be estimated with simulation capabilities for innumerable scenarios. This is mainly due to the tremendous work of national standards codes on fire safety and the work of fire laboratories for the last decades across the world. Many fire phenomena have now the possibility to be simulated in a validated manner with standard methods of testing for validation.

2. DESIGN AND PRODUCTION PROCESSES

Over the past decade, the ship building industry has begun to develop and apply Single Product Models (SPM) for improving the management and efficiency of design, analysis and production of commercial and naval vessels. SPMs are extensive single 3D CAD data models incorporating hull structure, propulsion, steering, piping, electrical, HVAC and other systems, which make up a complete ship. Ship classification societies and navies (most notably the USN in their DDX project) have ongoing R&D efforts to bring this technology to its full potential. This work involves leading software providers, including Tribon, Intergraph, Catia and ShipConstructor who are developing products, training and documentation to facilitate the use of SPMs by ship builders and design authorities. It is reasonable to expect that future vessels will be designed and built using SPMs.

There is strong interest by ship owners and agencies (including navies and ship classification societies) and the SPM software producers to extend the SPM applications beyond design and production to the lifecycle management of ships and offshore structures. This offers significant potential savings in operation and maintenance costs as well as improved understanding and confidence in marine safety.

2.1 The Design Process

The tools and techniques used to design ship structures have evolved over the last forty years from producing blueprints on the drafting board to the digital design of today. As computer technology became more powerful and relatively less expensive, computer-aided-design (CAD) systems evolved to support the design of complex products. CAD and other related tools empower designers and engineers to create innovative products more quickly and efficiently.

During the 1990's, the single product data management systems continued to expand in scope and scales. Companies recognized that they could use these systems not just to design their products, but also to manage the product data over the entire lifecycle from concept through deployment. At the same time, CAD and computer aided engineering (CAE) technologies grew in complexity and capabilities.

Less expensive hardware and more powerful tools provided the incentive for many companies to move from 2D CAD to 3D, the prerequisite for many analysis techniques like the finite element method (FEM). Once limited to mainframe computers, these powerful analysis tools also moved to the desktop, putting the full range of CAE at the engineer's fingertips.

2.2 Bridging the Gap: SPM Systems and Lifecycle Management Tools

Developing links between SPM databases and analysis tools used in the design process will undoubtedly reduce the effort currently required to perform assessments of marine structures. However, in order to develop this link, issues related to CAD interoperability, or the ability to share a CAD model across different applications, must be addressed.

Hidden errors and anomalies in the originating CAD data representation, as well as translation issues, often result in numerous problems and frustrations for the downstream users. While the emergence of standards such as STEP has helped reduce some of these problems, true interoperability is still far from reality. Some of the issues that affect data exchange from one CAD system to another are:

- Model quality in the originating CAD system: Many times the original model itself is of poor quality. Common problems include missing parts, invalid definition, and lack of connectivity (poor connection definition with neighbouring structure). These problems could be due to user error, numerical limitation of the CAD system, and/or design requirements. Many CAD models work well for design and drafting, but they do not have the quality required for structural finite element meshing operations.
- Semantics: Each CAD system does some customization to enhance its

primary objectives. This leads to differences in the way a data type is interpreted by each package. Thus, when a model is moved from one system to another, inaccuracies can be introduced due to mismatches or poor communication.

- Differences in tolerances: Geometric data is often in parametric form, accurate to the order of the specified tolerance. Differences in tolerance introduce gaps and overlaps in the model that can lead to problems when attempting to generate finite element meshes.
- Limitations of translation: Inaccuracies are introduced by translation errors. Often all the data types of a CAD system do not have a one-to-one mapping with the standard formats used by translators, so approximations need to be made. Approximations are also applied when converting data from the standard translator to the format used by the receiving system.

While fixing problems at the source (i.e.: within the original CAD representation) yields the best results, it is not always possible to do so. Finite element analysts usually do not have control over how a model is first created, so they are forced to deal with problematic CAD files. As a result, tools must be available to make repairs to imperfect CAD models. Common types of repair operations include:

Healing: Healing is designed to automatically detect and repair geometric and topological inaccuracies in the imported model by performing the following operations: (1) simplifying data by converting spline surfaces to analytic surfaces (i.e.: cylinders or spheres) wherever possible; (2) correcting topological problems by stitching; and (3) bridging gaps between boundary curves and surface data by re-computing intersections after extending the surfaces. Healing should also support the automatic detection and removal of sliver faces and short edges during import.

Tolerance modeling: Tolerance modeling addresses problems associated with inaccurate data or "leaky" models (with poor connectivity between neighbouring elements, such as surfaces) and provides the framework for model healing and data translation. Since poor connectivity may be an issue when a small tolerance is used, this tool increases the tolerance in problem areas, generating less precise, yet connected geometric elements. The less precise geometry can then be used to create valid topologies for mesh generation. Tolerance modeling does not assume (or require) that the geometry agrees with the topology, and takes the geometric error in the topology into consideration during modeling operations and calculations.

2.3 Hullforms

A recent review of the literature demonstrates significant interest in advancing the integration of CAD data into the ship design process. Roh (2007, 2008) published a pair of studies which looked at improving ship design practices using a 3D CAD model of a hull structure. As Roh suggests, often (during the initial stage of ship design) a 3D CAD model of the hull structure is not generated because of effort involved.

Unfortunately, in the absence of this model, a designer must manually calculate the production material information of a building block by using 2D drawing and parent ship data at the initial planning and scheduling stages. In order to reduce the level of effort required to produce this data, Roh has developed a methodology and supporting tools which allow users to easily generate the hull structural model at the initial design stage. The applicability of the proposed method was demonstrated by applying them to a deadweight 300,000 ton VLCC.

Lu (2005) presented a study which focused on the application of a single NURBS (Non-uniform Rational B-Spline) surface for the purposes of representing a sea-going ship hull. Several typical full-scale ships' hulls were modelled using this technique. In a series of papers which also looked at the application of B-spline surfaces in ship hull design, Pereza and Suarez (2006, 2007) presented an approach designed to create developable NURBS surfaces. Developable surfaces can be formed from flat sheets without stretching or tearing and with a minimum use of heat treatments, so the forces required to form sheet materials into developable surfaces are much less than for other surfaces and the construction costs are lower. Tauseef and Ding (2006) also examined the application of NURBS. In their paper, they describe a hull fairing process based on the use of a NURBS ruled surface method (Cross-Fix Method).

2.4 Structures

Jang *et al*. (2008) describe an algorithm capable of generating a finite element representation of a ship structure using a 3D CAD model as the primary source of geometric data. The algorithm is based on what the authors describe a Hold Analysis Integrated System (HAIN System) and a Whole Ship Analysis Integrated System (WAIN System).

The HAIN System includes:

- Interface with CADRA/GS-CAD
- Automatic FE modeling for cargo hold
- Automatic load generation module
- FE model and load check module
- Automatic reporting system

The WAIN System includes:

- Interface with GS-CAD
- Seakeeping analysis
- Design wave decision module
- Automatic FE modeling for whole ship
- Load generation module from seakeeping results
- FE model and load check system

The basic concept of their approach is to decompose surfaces using stiffener lines into sub regions and generate the finite element mesh using rules based on accepted finite element modeling practices.

2.5 Novel Techniques

In a paper published by Tann and Shaw (2007), a web-based object oriented design support system is described. The main objective of this approach is to speed up design and production times. In terms of parametric design, if a problem arises and, according to the authors does not exhibit complex spatial requirements, there could be a possible solution template that can be altered to address the specific designs. If this could be developed into a system it could save a significant amount of time. The authors provide examples that have reduced costs for companies around the world.

Schachter (2006) published a paper describing a design process approach named "solution focus design". According to the author, this method was first created in a context where the decision of what concept to be adopted supersedes the use of the classical design spiral, suggesting a combination of the spiral with morphological charts. The advantages are in terms of allowing for the introduction of creative ideas into the conceptual design process, eventually leading to an innovative product or design solution.

Woods (2006) investigated the "power of ambiguity" and its use in conceptual design. According to the author, there is a common link between the coefficients and ratios used in technological design (Naval Architecture) and conceptual sketches used in the artistic design of vessels. Both sets of attributes can act as pre cursors to design, each do so in entirely different ways.

Birk (2007) reported on the continuous development of an automated optimization procedure for the design of offshore structure hulls. The paper summarizes the new developments in the shape generation, illustrates the optimization procedure and presents results of the multi-objective hull shape optimization.

2.6 The Production Process

Roh and Lee (2007) describe a methodology for generating production material information using a 3D CAD model. According to the authors, a 3D CAD model for a whole hull structure is generated first, and the block division method for dividing the 3D CAD model into a number of building blocks is then developed using the relationship between the hull structural parts. In order to evaluate the proposed methodology, the authors applied the technique to a 300 000-ton very large crude oil carrier.

Hsu and Wu (2006) published a study on production-oriented design for the Capsize bulk carrier. This article was largely focused on the reduction of man-hours and steel in ship construction. The reduction of steel and man-hours was addressed by replacing the longitudinal reinforced pipe duct (LRPD) with a transverse reinforced pipe duct (TRPD). By doing this it is suggested that the number of steel pieces is reduced, and as a result, the man-hours required is also reduced. The TRPD are able to reduce the number of steel pieces because, "it has a thicker (outer) bottom, inner bottom, and girder plates, its rigidity is greater than the LRPD". The article steps the reader through equations that relate girder depth and deflection due to shear. It shows that the greater the depth the less resulting deflection due to shear. With the TRPD having a thicker plate than the LRPD, the TRPD will have less deflection.

The use of TRPD was tested by using ABS's SafeHull software tool. The most critical load and boundary conditions were applied to a triple hold model using both types of ducts. The analysis was then completed and showed that the TRPD had less deflection and exhibited less von-Mises stresses than a model with LRPD. The reduction in steel weight is not as significant as the reduction in steel pieces thusly saving man-hours.

Okumoto *et al*. (2006) published a paper dealing with simulation-based ship production using 3D CAD data. The article is largely focused on the use of three-dimensional CAD to improve production by simulating preconstruction, speeding up data modification time, and erection planning. By simulating the preconstruction, the construction becomes more effective and the completion of a project much less to do with trial and error. By being more effective in the construction, the material costs also can be reduced. In addition, the modification time can be reduced, saving time and money, by updating the modifications via the 3D CAD program. It is also stated that there is a reduction in lead time since materials can by calculated and order electronically and the skilled labour can be replaced by automation.

The article also states that with regards to ship production, simulations may be applied as follows:

- Analysis and evaluation of the production process
- Planning and assisting with production
- Training workers in such skills as line heating, welding, and straightening
- To confirm the safety of work operations

The use of CAD in construction can also largely assist installation abilities. The example of the use of scaffolding and mechanical lifting devices are aided by 3D CAD since the scaffolding can be planned before hand and the problems that arise during scaffolding construction can be avoided. In short, 3D CAD allows for planning at all stages to improve quality, safety and money (Yasuhisa, *et al*., 2006).

In a recent papers by Huang et. al. (2007, 2008), a description of a methodology focused on the problem of buckling distortion is provided. For the purposes of this study, buckling distortion is due to butt welding thin steel pieces together. This welding causes compressive stresses in the steel and since the thin steel does not have the strength to resist these residual stresses it buckles. In order to prevent distortion, the authors suggest the use of transient thermal tensioning (TTT). As the stiffeners are being welded, two heaters travel along the plate with the welded in the zones where compressive residual stresses are induced. The heat causes tension in these zones counteracting the compression. The intensity of the heat and the speed of the heaters vary with the thickness of the steel. In one test involving simple 5mm thick panel the TTT was found to totally eliminate the buckling but was not able to eliminate bowing in the steel plate. In another test with 10mm complex welding, the TTT decreased the buckling by 50%. This test also included small 3mm precision fillet welds.

Reverse arching is also a way of reducing residual stress. By applying a bending action to the beam and plate the compressive residual stresses are countered by tension and once welded the bending is eliminated. This was found to reduce the one third of the original stress and increasing the buckling strength.

3. INFORMATION TECHNOLOGY

In the previous ISSC 2006 report, the committee documented the underlying principles of collaboration and communication procedures implemented in a variety of software systems to be used in distributed but concurrently working ship design and production network scenarios. Special emphasis was put on overall requirements and the role of standardization of product model data.

In the recent years it has been noted a slowing down on the development of the standard ship Product Data Model from STEP (ISO 10303) although a new AP233 Systems Engineering Data Representation is under development and currently in draft status. This Application Protocol shares some modules with the AP239 devoted to Product Life Cycle Support (PLCS) that was published on 2005.

3.1 Product Data Model Advancements

Although with a slower development of the ship Product Data Model, STEP based technologies are being used for other applications such as the management of ship repair data (Ventura and Guedes Soares, 2007). In the scope of the US National Shipbuilding Research Program (NSRP) the Integrated Shipbuilding Environment (ISE) Project has developed standards and tools and have demonstrated their capability for successful product data exchange (structures, piping, HVAC) during the design stage (Gischner *et al.* , 2006).

Non-standard data models continue to be developed to support production (Oetter and Cahill 2006), production planning and scheduling, virtual assembly (Wu *et al.* , 2007) and life-cycle maintenance, namely hull maintenance (Jaramillo and Cabos, 2006; Renard and Weiss, 2006; Cabos *et al.* , 2008) using mainly XML based technologies.

The product data models are being extended to take into consideration lifecycle data (Briggs, 2006; Kassel and David, 2007). Beadling (2008) proposes the adoption of Product Lifecycle Management (PLM) application software developed specifically for ship design and production that can be used in concert with solutions for collaboration, digital mockup and product data management developed for aerospace to bring about business transformation across all phases of a single ship or a class of ship's lifecycle.

Kassel and Briggs (2008) consider an alternate approach to the exchange of ship product model data based on general-purpose STEP application protocols. The objective is to provide the functionality defined in the shipbuilding application protocols using a combination of STEP AP239, AP214, and reference data libraries. It is expected that AP239 translators will soon be available, thus enabling the exchange of significant portions of ship product model data. Bentin *et al.* (2008) presented a product model that supports assembly, room and system views, using CAD data and Product Data Management (PDM) in order to enable the digital factory concept. DNV has presented a product model specifying a standardized vessel description for class work (Vindøy, 2008). The development of fast prototyping systems allows the designer to take full advantage of a product data model (Don *et al*., 2007).

Dalhaug and Hardt (2006) discuss the risks of handling digital information as a fundamental part of the communication base. If the vision is to develop a paperless and digital organisation, the challenge is to move from a paper based to a digital work environment in a controlled manner. A Public Key Infrastructure (PKI) is described as an enabler and a support to the vision by ensuring that the security of a paperless production environment is equivalent or better when compared with a paper based production. The issue of PKI relates to how electronic documents are secured in storage (short/long term) as well as in transit, to avoid breeches in confidentiality, integrity, traceability and availability, and how non-internal users of graded information can be authenticated in a secure manner. The results from a substantial feasibility study and an outline of the design of the technical solution and the suggested infrastructure are presented.

Renard (2007) describes the basic ideas to develop methods and tools dedicated to European cooperative naval (military) projects. The research project CADET and its software tools in particular shall support all decision steps recognized as contributing to the success of any naval cooperative project. They provide a common methodology, a common language as well as the same structure of information for all partners (navies and shipbuilders). Partners will be provided with a complete road map of the project, from initial navies requirements to final building in the shipyards. CADET tools are intended to support all decision steps which have been recognized as contributing to the success of a naval cooperative project.

3.1.1 Computer Aided Approval

Grafe and Cabos (2007) discuss Computer Aided Approval (CAA) needs, problems and opportunities. They define computer aided approval as a synonym for the review and approval of design and construction on the basis of digital documents and data model files. The ship design approval process today is to a large extent dependent on the checking against predefined rule sets, which leads to a higher efficiency compared to direct calculations procedures. Computer aided approval is designed to combine the flexibility of the simulation based approach with the efficiency of the rule based way of work. The needs, problems and opportunities when implementing the new approach by using ship product data from ship yards and supplier are described.

Eberwien *et al*. (2007) describe the implemented CAA process in more detail. During the approval process, digital documents and optionally associated data model files representing the ship structure or machinery systems or parts thereof need to be exchanged between the customer (shipyard, design agent, marine systems supplier) and the classification society. All documents supplied to the classification society have to be of a legal character. The class on the other hand has to check and subsequently approve the provided documents in an auditable manner and returns an approval document which again is compliant with all relevant legal requirements. Data model files, additionally provided by the customer, may be used by the class for supplemental information.

In order to guarantee consistency in the information exchange activities, all documents have to conform to a predefined standard. For this purpose, Germanischer Lloyd (GL) uses signed PDF container which is a standard PDF file containing attachments. While the digital documents technically make up the cover page of such a container file, the data model files are provided as attachments to the container. To turn the PDF container into an information source legally binding, it is digitally signed. By the digital signature the submitting customer takes over the responsibility for the consistency of the digital document and the data model data files within the signed PDF container.

To support customers using this standard for information exchange, GL offers two scenarios for the creation of a digitally signed PDF container. Provided the customer has means to create PDF files from his CAD data and to fill a PDF container, he may submit a digitally signed PDF container directly to the web portal of GL. In the alternative scenario, a customer may use a web application which supports the creation of a PDF container. The process is guided in a way that all documents and data model files attached to the container by this service are accompanied by an appropriate label, i.e. the sequence of pages within the digital document conforms to the standard. All pages are automatically bookmarked and named after the given labels. The web application service accepts PDF and DXF for forming the digital document body of the PDF container. All other formats are treated as attachments to the container. The PDF container created by the GL web application service is returned to the customer, the signature of the PDF container turns it into a legal document. This can only be done by the customer; therefore all services provided only support the physical creation of the PDF container.

At GL, the signed PDF container is fed into the fully digital based approval processes which consists of document registration and permanent storage, revisions by plan approval engineers and finally plan approval. The PDF container is annotated, marked and redlined by the plan approval engineer just as he/she would do on a paper based document. The result can be viewed by e.g. the free Acrobat Reader or other PDF viewing software. The customers have access to the annotations without the need of an extra software licence. Looking over the annotations of a PDF document is much more convenient than to examine them on a paper based document. All digital annotations of a PDF document are displayed by the PDF viewer within a separate navigation pane. The list of annotations not only serves as an overview but is also directly linked to markups or redlining objects within the digital document. Thus checking the remarks made by the classification society reduces to tabbing through a list and executing a display function for the annotation of interest.

Class approval processes in shipbuilding introduce additional and specific requirements for information management systems to be used in the ship design process. Ehrler *et al*. (2007) describe that currently these requirements are not sufficiently addressed by state of the art PDM/PLM software tools and solutions. Classification societies have to manage product oriented structures (as designed, as built), associated analysis and simulation data (FEM, CFD) and manifold relationships to external part catalogues and material databases. Additionally, the underlying information model has to be extensible and adaptable during production use in order to satisfy short term requirements from different certification projects.

In this context a "Technical Information System" (TIS) project at Germanischer Lloyd, based on PDTec's ice.NET platform is implemented. TIS integrates data models from various legacy systems and provides configurable XML and web service interfaces to associated simulation programs. In addition to the information model and system architecture developed it is presented how to provide functional prototypes within a short time frame and limited budget which enables process-specific organization of information in a networked, project oriented structures including access control mechanisms, tracking and audit support. On the basis of a project example the requirements driven extension of the data model with the UML based development tool ice.NET Studio is shown.

3.1.2 Integration

The challenges for integrating well proven, existing software with new programming paradigms in the context of a specific tool to simulate a new ship design e.g. in a bridge simulator is described by Abels (2007). To achieve this, a system kernel in Java application is combined with simulation tools written predominantly in FORTRAN. Especially in engineering, powerful and large simulation tools need to be integrated in a design environment. The simulation tools may be developed in different environments and with different philosophies while the integration of e.g. complex simulation tools from different sources into one design system still poses major challenges.

For an engineer, the procedural approach is easy to understand, because the behaviour of a computer program can be analysed and judged. It is found not useful to require that engineers who want to implement special design software have to be familiar with complex IT concepts. Instead, it is believed more practical to use a framework with a clear restricted functionality which allows implementing software with only a short training period. Aspects of user authentication and the management of privileges are identified to be very important while the distributed usage of product model data generates problems of information consistency if not handled correctly. Computational networks with high bandwidth worldwide allow distributed computing power and the exchange of ship product model data. Time consuming calculations may be executed remotely at dedicated computer centres.

The special requirements on software tools to support an efficient assembly process are described by Mütze (2006). The paper suggests that appropriate and integrated software tools can make the assembly process more efficient, provided that it is well developed in the following three main areas: early definition of a break-down structure supported by relevant analysis tools, efficient modelling of topologically connected structural members and the support of the assembly process by automatically produced documentation. The product data model should support a gradual build-up of continuously refined data in order to enable early estimates as well as accurate information from the analysis of the final model. The required tight links between the detail design and assembly modelling are realized by the CAD-System Tribon.

The integrated project execution and its influence on an engineering portal solution are described by Herrmann (2007) and Gwyther (2007) with a special focus on the approach followed by AVEVA. The Integrated Project Execution (IPE) is a strategy for different yard departments, design agents, classification societies, suppliers, engineering contractors and owners to provide them with a sustainable approach for a successful usage of the core of their business information. After an overview about the different IT integration solutions built in the past and present (EDM, Engineering databases, PDM, Data Warehouse Solutions) the main features of the VNET engineering portal as one if the two central modules in the AVEVA's IPE strategy are described. Emphasis is put on AVEVA's Product Lifecycle Management (PLM) strategy for the shipbuilding industry. It is pointed out, that within the commercial and naval shipbuilding sectors, there is a strong need for integrated solutions which address the same spectrum of functional requirements as conventional PLM, including data and document storage, workflow and process management, product structure management, application and data integration, and visualisation/collaboration. However, in practice, there are only very few shipbuilders today using conventional PLM solutions to address their lifecycle information management needs.

This failure to penetrate the shipbuilding industry has arisen because the industry has a number of defining characteristics which differentiate it substantially from discrete/repetitive manufacturing. These characteristics dominate the business processes and associated product data management requirements of shipbuilding organisations and ensure that conventional PLM software acquisition and deployment is either an unsuitable or sub-optimal lifecycle management solution. IT solutions designed as part of a PLM strategy are mostly and primarily focused on integration. Hence organisations in the capital project market designing a PLM strategy should firstly develop an overall strategy for an integrated project execution. Thus an integration solution will be an essential component and a foundation for each IPE strategy. For a better understanding of the term “information” in the context of PLM a closer look at the PLM definition as published by CIMdata, the independent strategic consultancy in the PLM business area is taken. CIMdata defines PLM as: "A strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from concept to end of life integrating people, processes, business systems, and information." To find a better way of using project related information and capitalising its value, the need to understand what the existing limits and constraints are is regarded as essential. Especially the project culture is identified as a major constraint that has to be understood in the context of information sharing.

Communication and co-ordination procedures in merchant ship design are described in Bronsart *et al.*(2006). Principal characteristics of the inter-organizational communication in the ship design phase are discussed. The implementation of a communication and information integration platform to support the collaboration of partners is presented. An integrated product data management system functions as an infrastructure to set up a coordinated and consistent project data repository. Examples on the ship product data exchange between software systems like NAPA steel, GL-POSEIDON and UNIGRAPHICS-NX serve to identify the potential of relevant ISO-standards (AP 214) in this context.

3.1.3 Management of Design Changes

Following this approach, the integration of partners involved helps to increase the awareness of the overall design process. As in other industries, the efficient and consistent management of changes of product and process relevant data in the concurrent and collaborative design process is considered of utmost importance. In several ship design communication scenarios analyzed, up to 80% of all communication events were due to changes on data representing the ship and/or systems and components thereof. With respect to the characteristics of the design process, the following statements are made: lack of infrastructures which support the effective and transparent change management in inter-organizational ship design scenarios, tools used in the ship design are not capable to manage versions and configurations efficiently, a prerequisite for engineering change management functions. Partners from the maritime industry interviewed see a great potential for savings by increasing the overall productivity through minimization of errors due to unknown or outdated product data. Formal methods being used in other industries are in most cases not suitable due to the very tight time schedules, the dynamic of the design process itself and the frequently changing partners in the ship design and production networks.

To support the management of engineering changes, the information management system developed offers all necessary basic functions: user rights management, versioning of information objects of any kind, logging mechanisms of all interactions, search functions which are capable to deal with multiple versions of information objects. Different engineering change management approaches which form the basis of these functions in PDM systems are listed. The most relevant ones are: Quality management - Guidelines for configuration management (ISO 10007), Institute of Configuration Management (CMII), Workflow Management Coalition (WfMC) and the ISO 10303 Standard for the Exchange of Product Model Data (STEP).

These (industry) standards have in common that formal procedures are defined which have to be strictly followed: an engineering change request (ECR) initiates a procedure in which the impact analysis is succeeded by the review of proposed alternative solutions. If the request is accepted by a specially authorized change management board, the change is implemented according to the chosen alternative solution and communicated to the partners involved. The change history at the same time is updated. In case the request is rejected, partners are also informed and the change history log is again updated for quality management purposes.

For the management of changes in collaborative ship design, two different procedures are implemented on the information server and the product manager client component. The first is compliant to the procedure described above. It is important to note that the final acceptance of a change request might depend on a number of predefined authorized persons, potentially from different companies making up the design and production team. A second method is realized which implements a different, far less formally defined communication principle. Due to the tight time schedules in ship design and production, changes to product data are often not made compliant to the formal, predefined procedures. For many, globally distributed partners involved, it is regarded important that they are informed in time about changes to product data relevant to their own work. Therefore, authorized partners can subscribe to automatically receive information if certain product data are modified or added to. By this they can keep up to date without the necessity to manually check for changes. To prevent information overflow, selection functions on a detailed level of granularity are offered. Additionally, the project manager can define information paths to inform partners about changes even though they might not have realized the specific importance for their own work. The result of these functions is that the information management system automatically triggers information events according to the formulated requirements and information flows.

3.1.4 Project Management Applications

A special focus on the requirements on software tools to support the collaboration in offshore projects is given by Cho *et al*. (2007). For offshore projects, the effective collaboration of engineers from different disciplines in various locations is of special importance. The product itself has numerous instruments and parts which make it very complex. Additionally the limited space available poses high challenges compared to onshore projects which are generally not limited in space. At any given time, up-to-date information sharing is essential. A web-based information management system is developed for this purpose. The Daewoo Shipbuilding & Marine Engineering Information Management System (DIMS) will facilitate information exchange among the builder, owner and vendors involved in the project. The DIMS offers three major functionalities. The Document Management System (DMS) functions to classify and preserve the project's engineering and vendor technical documents. Second, Collaboration functions are responsible for controlling the correspondence documents and their distribution. Finally the Asset Management System (AMS) handles the assets supervision for the project operation. The Asset Management System is used to manage engineering Bill of Material (BOM) of parts information and the same information is handed over to other systems. The three systems are integrated to perform sharing and exchange of information. The DIMS is developed to provide a reliable and efficient information management to the concerned parties regardless of their location and time throughout the project lifecycle.

It is emphasised that the success of an offshore project is mainly influenced by the communication management which can be seen from the fact that well over 100,000 documents and drawings produced for each phase for the entire life cycle of a project have to be managed. Web based information management systems are identified to overcome the problems produced by offline processes. By this the partners involved in a project team can access information at any time and anywhere simply using the Internet. Categorizing documents is convenient as well as sharing and searching of document information. Workflows are enhanced in close collaboration of the engineers.

According to Park *et al*. (2007) an engineering process management system has been developed, called the 'Daewoo Shipbuilding & Marine Engineering (DSME) Engineering Wizard System'. It aims to accelerate process performance by managing execution, promoting collaboration and maximizing engineering data reusability based on workflow concepts. For the application of this system, the marketing design phase, which is one of the major processes for commercial ship design, was analyzed and established into a unique workflow template consisting of several interrelated activities. Doing so the design experiences is organized into a best practice approach in which engineering tasks are performed in the way proven most efficient. The system is implemented based on the BRIX framework which DNV software provides.

Nedeß *et al*. (2007) describe the necessity of an efficient workflow support for ship development projects which is to be based on a suitable IT infrastructure. It is pointed out that made to order product development projects in the shipbuilding industry are especially complex as a result of the simultaneous design, fabrication and assembly.

This leads to the need of an extensive planning and coordination of processes during the whole project. In contrast to the well planned and structured fabrication and assembly, the design processes at a shipyard can still be improved for a better coordination, process overview and fewer inconsistencies. In order to achieve this, a new approach for coordination and control of development processes is considered to be essential. Workflow management is an approach to coordinate processes that has been used in other industries like the banking sector for many years. Possible application areas for workflow management in product development processes in the shipbuilding industry from the project management point of view are discussed; a model for individual workflow support for each process type is developed. A flexible approach for workflow management in product development based on workflow modules is derived. Supported by predefined workflow modules, it is possible to configure and adapt the different processes and their variants even during project runtime in a flexible way. Design and usage of the workflow modules are explained, the interdependencies between workflow and other development support systems (e. g. project management system) are discussed.

The goal of the Shipbuilding Partners and Suppliers Consortium (SPARS) is to re-engineer and replace manual, labour intensive, paper based, error prone, and long cycle interactions amongst shipyards, suppliers and the US NAVY with help of Internet based shipyard to supplier business processes managed by a workflow manager component (Bolton, 2007). This will reduce labour costs, error rates and cycle times and will also improve the overall business process visibility to enhance the management and tracking of information flows. SPARS enables organizations to collaborate and interoperate as a single "Virtual Enterprise" by removing inter-organizational business processes discontinuities and data inconsistencies. The shipyard-supplier business processes are re-engineered using LEAN principles. The results of SPARS work have been implemented at major US shipyards and supplier members and commercialized by the technology development members of the SPARS team. It is emphasised that SPARS has a track record of tangible results and operational solutions with demonstrated cost reductions and an overall return on investment of 3:1.

SPARS presents a comprehensive solution to improve shipyard and supplier business processes by organizing and instantiating the shipbuilding supply chain as a "Virtual Enterprise." Virtual Enterprise technology enables multi-organization, electronic-based business processes that are transparent of the underlying individual organization’s processes, computing environments and data structures. The SPARS solution set consists of the following major elements of a shipbuilding VE.: a Virtual Enterprise Server, Virtual Enterprise Client and several Virtual Enterprise Business Processes. SPARS is built on an open standards based architecture supported by commercial application and systems vendors.

To support future naval ship projects, the French company DCNS is developing an IT system generation with the objectives of a global integrated IT system allowing concurrent engineering with full digital mock-up, new capabilities including management of system engineering, manufacturing planning, highly constrained development planning. The system is called "Etrave" and its architecture is based on the extended enterprise PLM software (WindchillTM integrated with different CAD tools such as SEE VISIO TM for the 2D schematics diagrams, CADDS5 TM for the 3D models). A vision of the future needs in terms of IT technologies for shipbuilding is presented, Le Gal, *et al*. (2007).

Polini and Schmidt (2007) also point out that one way to reduce lead time in ship design is to subcontract all or some portion of the work to external partners at both the design and production levels. This solution affords flexibility in workforce utilization compared to the alternative of hiring more resources and at the same time it has a potential cost saving aspect. The enabler for such an environment is seen in a design system that supports a process whereby it is possible to manage globally distributed projects from a centralized location without using excessive additional efforts in coordination and control activities. The major functional components of such a design system are described with respect to configuration, access control and data interoperability requirements.

Key collaborative capabilities that are required for shipbuilders to meet the design and build challenges of both naval and commercial shipbuilders are discussed by Donoghue *et al*. (2007). The benefits to shipbuilders of adopting a collaborative design, visualisation, and manufacturing environment are presented; case studies from a number of naval and commercial shipbuilders serve to illustrate this. A special focus is on the business improvements that can be gained by addressing the process and technology related issues generated by the challenges of implementing a single integrated 3D digital mock-up and Product Life Cycle Management system across shipbuilding partnerships based on PTC's product centric development system.

3.1.5 Replication and Sharing

Cahill (2007) points out that ship product data modelling systems are continuously becoming more complex as they attempt to encompass all design disciplines at every stage of design and include information to support material procurement, production and ship lifecycle management. Therefore the databases that are developed in the design phase are growing larger at an exponential rate. It is stated that this has only minor effects on database centric design systems as long as the design activity is based on a dedicated network, with high capacity bandwidth available. The Structured Query Language (SQL) replication technology is regarded as one solution to integrate all partners involved in the ship design process, regardless where they are actually located. This specially holds for organizations having a more comprehensive communications infrastructure and significant in-house information systems technology capabilities available. These organizations may be able to take advantage of the SQL replication technology recently developed and tested in a pilot project by ShipConstructor Software, Inc. Project replication using SQL server tools allows multiple databases that are connected with an "always on" connection to update each other. This can occur across domains, enabling remote sites to work concurrently on the same project with the databases at each site always maintaining consistency with the other databases.

Replication is done using a Publisher-Subscriber scenario. One site is determined to be the master database for the project and is set up as the publisher. Remote sites are established as subscribers. This creates a single point of control for the project, since subscribers are prevented from communicating directly with each other. A second approach is based on a split and merge concept with a shipyard defining a project setup including the work breakdown structure, part naming conventions, stock material items, major equipment items and other pertinent information that needs to be established at the start of the project. The entire project file directory, along with the database created for the project is copied and provided to the subcontractor(s), along with a work scope that defines the areas of responsibility for the subcontractor. A portion of the model is then "Split" off of the master model and assigned to the subcontractor to work on. This portion can either be an entire structural unit or a distributive system truncated at the unit level. The subcontractor develops the design for their assigned unit/system within the model, when an appropriate level of completion is reached the unit or system is merged with the master model. The splitting and merging is done at the database level. All changes to the data model occur in the database rather than in separate drawing files which cannot be shared for read and write by multiple users.

This approach is especially useful for design agents and shipyards that do not have an extensive communications infrastructure, dedicated high speed Internet lines, or skilled in-house IT personnel to manage servers etc. The splitting or merging is done incrementally at intervals determined in advance, and based on established parameters for completion prior to merging models. This does not require an "always on" connection between the master model and the satellite databases. Splitting and merging can be accomplished either with secure Internet file transfers or even by copying to removable media such as DVD and sending the media with the database and associated drawings.

The two approaches, concurrent and distributed work in ship design are analyzed by Alonso *et al*. (2007 a). Emphasis is put on a concurrent solution as the evolution of the basic technologies such as databases and communications infrastructures allow for an efficient network approach. A shipbuilding oriented 3D CAD/CAM system, integrating the whole ship product model in a single database, facilitates the necessary coordination between the different design agents. In this respect, the experience of SENER is described. Tools have been developed to adapt a relational database as well as the associated database management software to a remote concurrent design environment making use of database replication techniques. From a shipyard perspective, as the owner of the information, other issues are to be solved additionally, such as the control of access to restricted parts of the project due to both confidentiality reasons and the maturity of the information already stored. The scalability of the implementation is analyzed in order to test the performance of the described solution in an environment involving a large number of users simultaneously.

The use of replicated databases is also investigated by Alonso *et al*. (2007 b) as a solution to facilitate the collaborative engineering in the same project of two large working groups geographically separated. It reduces the needs of coordination for the same working groups working with independent databases. Working in a replicated environment requires the use of a suitable communication infrastructure between the two replicated sites, especially as refers to the latency of the network. The advantage of the proposed solution is that it can be combined with other, especially with the Terminal Sever Approach and with the remote access to the database, so allowing for configuring the most appropriate solution for each collaborative design environment.

3.2 Product Model Data Quality

The aim of the research and development project QualiSHIP is to improve the quality and productivity of the ship design and production process by developing knowledge based tools for an automated quality control of product model data (http://www.qualiship.de). To make a tool usable at any step in the design process, e.g. before data are exchanged between different tasks (in-house or between companies), all intra- and inter-organizational processes are to be supported. The QualiSHIP project partners are two shipyards, working with different CAD-systems and building different types of ships: FR. Lürssen Werft and Wadan Yards Germany. Together with the design agent SMK-Ingenieurbüro intra-organizational vertical and horizontal data exchange scenarios based on different CAD-systems, as well as the inter-organizational exchange of product data at different stages in the design process are performed. Atlantec Enterprise Solutions contributes to the project with its neutral data repository and integrated rule engine implementation. The Center for Marine Information Systems (CeMarIS) at the University of Rostock is responsible for the rule based checking procedures and rule formulation. Germanischer Lloyd adds to the scenarios by implementing computer aided approval procedures and corresponding data quality control procedures.

To increase the ship design and production productivity it is widely acknowledged that ship product model data errors of any kind should be detected and corrected as early as possible in the process chain. The exponential rule states that the costs for the error correction increase by an exponential function: at each phase further downstream the process chain between error origination and detection, the exponent of the cost function increases by more than one.

To supply the engineers with a tool to detect errors and/or data quality problems as early as possible, a software system is developed which allows for the formulation of quality criteria with which the ship product model data must comply. An automated check of the product model data against the formulated criteria results in a report which gives advice to the engineers on how to improve the actual product data model. Figure 3.1 shows the results achieved from the process analysis. It is shown that today the majority of errors obviously originate from the detailed design. However the majority of design problems are detected not until the production phase. The implementation of an automated quality control procedure will shift the error detection upstream and therefore contributes to substantial cost reduction and time savings.

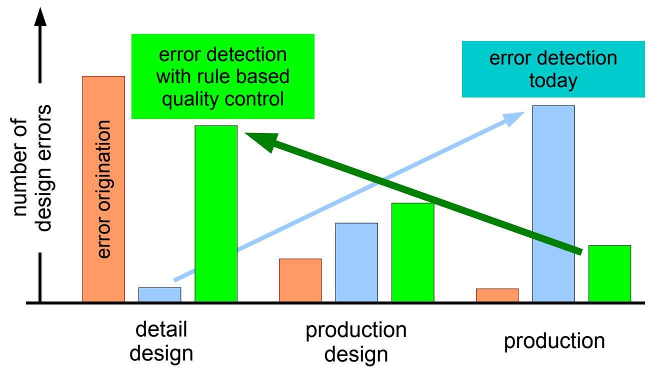


Fig. 3.1: Quality control of ship product data results in an upstream shift of error detections

For the complete process analysis, the ship design process is split into five main phases: project planning, basic design, detail design, generating of manufacturing information, and finally, manufacturing. During the planning and design process phase, a ship product data model is created which is being constantly developed and revised. At different stages drawings are derived from the 3D-model and submitted to e.g. the classification society for technical surveillance or passed on to manufacturing preparation. The product data model in any case forms the fundamental basis from which various kinds of manufacturing information are derived. Throughout the overall process the data representation undergo a large number of exchanges, conversions, and redesigns due to changes. This causes the fundamental risk of information loss and/or corruption. As the consequences of errors become more and more serious the later they are discovered, it is crucial to check the product model data as early as possible to make sure that the 3D model data are correct, consistent and fully represent the actual design stage. Having a tool to cross check the derived data with the "truth" represented by the 3D product data model will ensure the data quality and will therefore contribute to reduce costs for expensive corrections in the downstream manufacturing processes.

For many ship projects design work is subcontracted to external design agents. As design agents usually work for multiple shipyards at different levels of cooperation with different CAD-systems and different shipyard specific standards and demands at the same time, the engineers constantly have to observe different project settings which are crucial with respect to the quality of their design work. This situation increases the probability of errors substantially. A tool to check the product data for consistency with predefined rules which are configurable for each project will generate a higher reliability of the product model data and therefore will contribute to increase the efficiency in the cooperation.

3.2.1 Quality Control for Ship Structures Data Models

To define the fundamental requirements on the quality of a ship product data model, shipyards and cooperating design agents were interviewed. Engineers involved in the design as well as the production process or being responsible for these processes reported actual problems according to their specific knowledge and experience. To limit the number of process steps in the scope of the survey and to narrow down the amount of data to be checked in the design process, only those tasks which are affected by errors and at the same time have a major impact on the overall performance were taken into account for further consideration.

The information given by many experienced engineers from several maritime companies utilizing different well known CAD-systems was fed into a data base. The data base finally comprehended more than 180 “typical problem types” occurring in the different phases of the ship design process and at the multiple interfaces between them. The documented problems can be classified into six major types:

Identification Attributes: problems concerning attributes in the 3D product model serving to identify parts,
Material Logistics: problems caused by not observed limitations in raw material and stock material,
Manufacturing Requirements: problems caused by not observed requirements from the manufacturing of parts and specially assemblies,
Weld Preparation: as an important subset of category above found worth for a separate type category: special problems occurring at weld preparation,
Design Practice: problems caused by not observing state of the art design solutions in specific design contexts,
Drawing Conventions: problems due to the neglect of conventions for drawing.

These problem types are further subdivided into sub-categories each with a focal point allowing to further classify the identified problems. This approach finally resulted in 24 principle error types occurring in the design and manufacturing data generation of naval and commercial ships.

The error analysis furthermore revealed that four general criteria: a) *existence*, b) *compliance with predefined conventions, standards*, c) *conclusiveness* and d) *consistency* can be identified which are generally to be fulfilled. The application specific problem types and the four general criteria result in a matrix in which all quality criteria are documented.

As an example the criteria for the identification of parts in form of position numbers is briefly discussed – this criteria is judged to be of high priority for an automated quality control process. Although there are many different, partially complex structured rule sets to be considered, the “position number” quality criteria are simple examples which will serve to explain the general quality criteria in this context.

As engineers normally work on several projects with different requirements at the same time, it was found a challenge for them to observe all specific conventions and relevant parameters for each project consistently. All CAD-systems used to generate the product model data offer sophisticated and efficient functions to set position numbers for all kinds of parts. Using these functions can however result in a parts numbering which is not correct with respect to the project specific conventions. The four general criteria for this example can be used to formulate the following quality criteria to be observed:

Existence: This criterion obviously is very simple and can be formulated straightforwardly: Every part must have a position number assigned to it. Parts with no position number will cause potentially major problems at the latest in the production preparation process.

Compliance with predefined conventions: Position numbers have to be conforming to yard or project specific conventions according to a specific naming and/or numbering system. Examples found for position numbering are: Each part type gets his own range of numbers (e.g. plates from 300 to 399, stiffeners from 400 to 499 etc.). Position numbers are four digits and have to begin with the figure “1” for profiles and plates. Standard parts like brackets or clips have their own unique number, some are project specific and some are identical for all projects. The representation of position numbers on drawings has to follow specific requirements (e.g. usage of a combination of symbols and digits).

Conclusiveness: This criterion formulates requirements on position numbers of one part in relationship to other parts: parts not being identical are not allowed to have the same position number assigned to. However it was found necessary for some projects that due to the production process applied, identical parts can have different position numbers assigned to. To determine the identity of parts, the shape formed by the inner and outer contours and the material type have to be analyzed thoroughly. Especially for an exact shape analysis observing allowed tolerances, the identity check of parts requires the application of complex, sometimes time consuming geometrical and topological algorithms.

Consistency: The three criteria listed above are formulated with respect to ship product model data represented in a 3D-product model. In case of multiple representations of these data, e.g. additionally in drawings and derived manufacturing information in text files or spread sheets, the consistency between these representations has to be ensured: e.g. the position number for every part has to be the same in all representations of that part. Resolution of conflicts of this type is still a major challenge which results in time consuming and error prone engineering change management tasks.

3.3 Rules and Rule Engines

The quality criteria are to be formulated with respect to the product data model created by a CAD-System. Due to the major objective of the project *QualiSHIP* – the independence of quality control mechanisms from the CAD-System – several interface programs etc. using different data access mechanisms and programming languages would have to be implemented. Using a Rule Engine instead, important advantages compared to individual and manual programming can be identified: Declarative Programming: Rule engines allow the formulation of "What to do" and not "How to do something".

The key advantage of this feature is that using rules makes it easier to express solutions to difficult problems and consequently apply these solutions. Rule systems generally are capable of providing explanations for how the solution was derived and why each "decision" along the path was made. *Logic and Data Separation*: Data are stored in domain objects – in this case the ship product data model. The logic however is represented by formulated rules. This approach is fundamentally different from the object oriented approach which is based on the direct coupling of data and logic.

Contrary to the object oriented approach with storage of data in form of attributes of an object and the corresponding logic in form of methods, in a rule based system both will be stored in separate repositories. The result is that the logic can be maintained easier which is especially the case when the logic is cross-domain or multi-domain. Instead of the logic being spread across many domain objects, it can all be organized in one or more rule sets. *Centralization of knowledge*: By using a rules based approach for representing domain specific knowledge, in this case representing the quality criteria for ship structure data models, a repository of knowledge is created which can be maintained, updated and added to separately from the ship product data.

The term "*Rule*" originates from formal grammar: it is an abstract structure that is described precisely by a formal language. A rule can be interpreted as consisting of a two-part structure using First Order Logic for the knowledge representation: `when <conditions> then <actions>.` Rules can be dependent on other rules, however calculating the order of execution is a central function of the Rule Engine and therefore has not to be managed by the engineer formulating the rules.

The term "*Rule Engine*" can be defined as follows: For any application for which the business rules change more frequently then the rest of the application code, Rule Engine or Inference Engines are the software components that separate the business rules from the application code. This allows the business users to modify the rules frequently without the need of IT intervention and hence allowing the applications to be more adaptable with dynamically formulated rules.

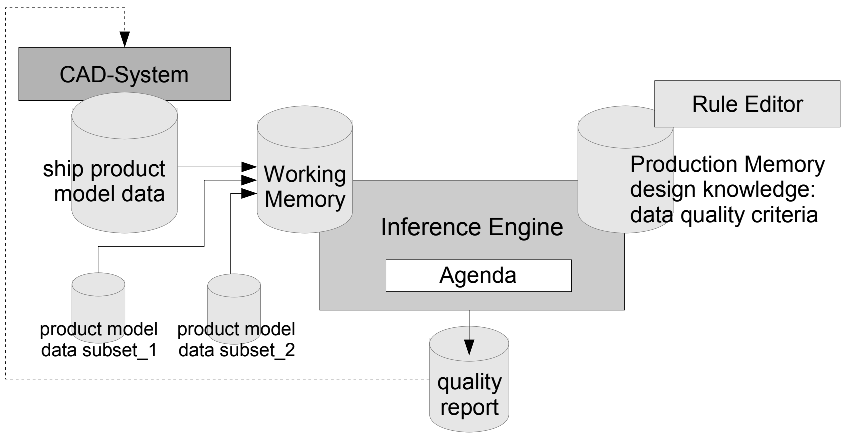


Figure 3.2: Basis Architecture of an Integrated Rule Engine

Figure 3.2 shows the main components of an integrated Rule Engine. Two repositories are to be distinguished: the Production Memory and the Working Memory. In the Production Memory all rules defined for a given context are stored: e.g. the quality criteria to be applied for the ship data model. The facts are stored in the Working Memory. Facts are all data which will be checked or potentially modified by rules: the ship product model data. The major component of the Rule Engine is the Inference Engine that matches facts (data) against the defined rules, to infer conclusions which result in actions. The Agenda is an additional fundamental component of the inference machine which manages the execution order of conflicting rules using a conflict resolution strategy.

3.3.1 A Rule Engine for Quality Criteria Checking

To select the optimal solution for a rule engine in a specific application context, the definition of system requirements for the relevant design and collaboration scenarios is essential. For the quality control mechanisms to be applied for ship product model data the following requirements were identified having a high priority in the selection process: Qualified engineers should be able to formulate even complex quality criteria with help of the software system to be implemented. Therefore the syntax of the language for defining rules expressing ship design knowledge should be human readable and easy understandable. The quality control system should be integrated efficiently in the existing software infrastructure at e.g. shipyards and design agents. As this is achieved best with a network approach, it is essential that the underlying programming language supports this approach: the server component should therefore be implemented using Java Enterprise Beans Technologies, including the JBoss Applicationserver. Finally the overall system should be as simple as possible with respect to the development as well as to the maintenance.

According to these requirements the rule engine JBoss Drools was chosen for the implementation. As part of the JBoss Middleware it is automatically integrated in the JBoss environment. It offers an interesting feature in form of a Domain Specific Languages (DSL). The DSL can serve as a layer of separation between rule authoring and the domain objects that the Rule Engine operates on. DSLs can also act as templates for conditions or actions that are used in different rules with changing parameters. If rules need to be formulated and validated by domain experts e.g. naval architects, DSLs are a method to ease these tasks substantially. Due to the internal implementation DSLs have no impact on rules at runtime.

The integrated rule engine implementation has proven that the quality of ship product data can be checked efficiently at any time while making use of rules representing criteria independently from the ship product model implemented in specific CAD-systems, Bronsart (2008). The rule engine can be configured to generate a report in which the result of a specific check run is documented. Statistical data such as the total number of parts, the overall percentage of parts violating selected rules or for each quality criteria the number of parts violating the criteria serve to judge upon the overall quality of the product model data selected for the check. Additionally for every part a detailed status is given listing all violating quality criteria including a severity index which helps to identify the most severe problems detected. The rule based system does not require special computer equipment: a complex assembly structure specially defined for test purposes can be checked against a rich set of defined quality criteria in a couple of seconds on a standard PC. A set of assemblies consisting of about 8000 ship structure parts being “correctly” modelled with help of a CAD-system were checked resulting in more than 1000 violations of the quality criteria on position numbering, notches and plate edge bevel for weld preparation and required excess material at block boundaries.

According to the experience gained, two major aspects have to be considered especially in the future: some of the identified high priority quality criteria are too complex to be checked automatically based on the existing ship product model data implemented in CAD-systems. These data models do not hold attributes or relationships between information objects which are necessary for a thorough data quality control procedure. Furthermore the formulation of quality criteria requires a sound knowledge of the whole system architecture in use which in many cases is not available to the engineers focussing on specific ship design tasks. Apart from these challenges, first tests have shown that even for criteria being formulated easily, the gain in data quality can be substantial.

4. MAINTENANCE AND REPAIR

Complicated demands from many aspects must be considered during design process. Design for better maintenance and fewer, less costly repairs is one of the critical issues for designer. A specific important issue which should be considered for maintenance and repair in the design stage is to provide means of access for maintenance and inspection of critical hull structural parts. SOLAS's requirement for PMA (Permanent Means of Access) had been discussed in previous committee VI.2 reports. This regulation provides means to enable overall inspections, close-up inspections and thickness measurements. Some permanent passages should be arranged for maintenance and transportation of large facilities on board. It is especially important for smaller vessels, as their main engines often have to be moved off the vessels for maintenance and repair.

4.1 Hull Condition Monitoring

Feedback from monitoring marine structures in actual sea environments is a very effective way of calibrating and verifying structure design methodologies. Structural fatigue is one of the most important phenomena to be studied in this manner. Wave induced high frequency hull girder vibrations, denoted as springing had been discussed in previous committee II.2 reports. The effects of springing increase as ships become larger and more flexible, and ships can quickly consume their fatigue lifetime when serving in harsh environments like the North Atlantic routes.

The condition monitoring of hull structures has always been a prime concern of all Classification Societies and methods of accomplishing real-time assessment have been featured in continuing research programs. DNV has recorded global vibrations of several large sea going vessels by hull monitoring systems. Storhaug & Moe (2007) proposed the onboard measurement results of a 4,400 TEU Panamax container ship, the preliminary results indicated the fatigue damage was 4.8 times worse than the average expected according to design. This research also indicated that wave induced vibration ought to be included in fatigue design for a container vessels with optimized scantlings in order to avoid additional repairs during service life. As container ships keep increasing in size because more capacity tends to improve transportation efficiency, it is expected that more cumulative fatigue damage due to springing induced stress cycles may jeopardize fatigue strength. This is a concern for current ultra-large container carriers if suitable measures are not taken in the fatigue design process.

Recently, Lloyd's Register of Shipping (2008) carried out trial studies using a small product tanker and a double hull Aframax tanker as a means of assessing the feasibility of an acoustic emission approach to hull condition monitoring. These trials have shown that acoustic emission detection of active propagating fatigue cracks together with their location is a viable technical tool and general hull monitoring is possible using a sufficiently large array of sensors.

ABS (2007) introduced the guide for hull inspection and maintenance program to assist owners with the development of a reliable maintenance program. Using pro-active steps with scheduling of maintenance, the program supports the implementation of a proactive hull maintenance complying with self imposed standards and the requirements in conjunction with the normal classification surveys.

Takano *et al*. (2006) proposed a pro-active safety management system for ship structures that quantifies aging effects. This new approach to the ship's structural surveys assesses the effects of fatigue and corrosion on the ship's structural integrity. In this system, the core tool of the hull aging management system (HAMS), a fatigue damage evaluation method employs fatigue damage sensor (FDS) systems. The system is presented by Ohmichi *et al*. (2007) and was developed for the acquisition of data on accumulated fatigue damage in a simple and practical way (see Figure 4.1).

Requirements for CAP and TMSA compliance are important in order to obtain acceptance by charterers. Transparency and continuous control of a ship's hull condition may create business advantages to ship operators and owners. Lovstad (2008) applied DNV's HIM (Hull Integrity Management), a tool for owners and operators to LPG carriers. In HIM, three dimensional illustrations of Hull Inspection Manuals give image descriptions that make the virtual reality very close to the real image onboard as shown in Figure 4.2.

Jaramillo (2008) gives an overview of hull condition monitoring (HCM) and assessment of thickness measurements in conjunction with GL's Hull Life Cycle Programme. The Hull Life Cycle Program utilizes 3D-models of the vessel for monitoring the hull integrity of a ship throughout its entire life cycle.

4.2 Reliability Based Inspection and Maintenance

Kawamura *et al*. (2006) proposes a new method for rational decision making of hull maintenance planning for a ship. Both the allowable level of safety and cost of maintenance are discussed. In this method, a proper hull maintenance plan can be selected by maximizing the remaining life benefit (RLB) computed considering the survey results and the risk of failure of the ship. By computing results of RLB for a bulk carrier, it is noted that higher RLB values are not always given by frequent repairs whereas, in general, lack of repair gives much lower values.

Kaminski (2007) presented a methodology for studying the crack appearance in FPSOs By comparison of the predicted and the actual factors influencing fatigue loading. The work includes a discussion of fatigue design practice, describes the need for documentation of the predicted factors at the design stage. A hydro-structural monitoring system called the Advisory Monitoring System (AMS) is described and recommended as a methodology to guide the inspection, repair and maintenance programs for FPSOs.

Risk- and reliability- based approaches are regarded as very powerful tools to help optimize an integrity program and offer flexibility in helping manage structural integrity. Lee *et al*. (2007) presented a multilevel risk based inspection methodology. This effort, ranging from simplified deterministic approaches to sophisticated probabilistic approaches, was successfully applied in inspection planning for several FPSO installations.

4.3 Performance Standards for Protective Coatings

Corrosion is one of the most important factors influencing safety and integrity of aging structures. Melchers (2007) and Paik *et al.* (2008) introduced some recent developments in corrosion assessment and management for steel ships and offshore structures, and presented relevant corrosion mechanism, corrosion wastage models, design discussions, and preventive measures for marine structures.

Performance Standards for Protective Coatings (PSPC) for water ballast tanks and double hull spaces of bulk carriers were adopted at MSC82 as the Resolution MSC. 215 (82) in 2006. Protective coatings for void spaces are also adopted voluntary. Furthermore, protective coatings for cargo oil tanks have been discussed at the Joint Working Group of IACS. Performance standard for protective coatings are valid for protective coatings in dedicated seawater ballast tanks of all types of ships of not less than 500 gross tonnage and double-side skin spaces of bulk carriers larger than 150 m in length. PSPC had entered into force for ships for which the building contract is placed on or after 1 July 2008, or, in the absence of a building contract, the keels are laid on or after 1 January 2009, or if the delivery is on or after 1 July 2012.

The new regulation is stringent and may have a great impact on shipyards. According to the estimation of Shipbuilders' Association of Japan, the quantity of production output will be reduced by about 20% and the man-hours for painting will increase by more than 50%. Unfortunately, there are not many measures that can be taken at the design stage to improve surface treatment and yard productivity. Some typical countermeasures are described as follows:

- Less block joints to be located in ballast tanks: it is almost impossible to avoid block joints in ballast tanks for merchant ships, but it may be a solution for smaller vessels,
- Simplify structural details in ballast tanks: arrange stiffeners on the exterior side of tank boundary if possible,
- Use shape or section steel like bulb plates and inverted angles instead of built-up sections to reduce the time-consuming edge grinding treatments,
- Lightening holes to be greater than 400 mm, and drain holes to be as large as practicable.

Murakami *et al.* (2007) studied the coating conditions in water ballast tanks of ships more than 10 years of age. Based on inspection results, void spaces and cargo oil tanks, a discussion of the relation between tank coating at new building stages and the coating conditions of aged ships is documented.

PSPC stipulates “3-Pass or 2-R” edge grinding treatment prior to secondary surface preparation. Seo et a(2007) show most of excessive burrs located at the edges are removed during the ISO Sa 2-1/2 blasting stage before coating, and conclude the most favorable way to avoid overly thick coating at the edges (that cause coating cracks leading to corrosion problem) is to maintain proper balance between edge preparation and stripe coating to ensure sufficient edge retention of coatings. Osawa *et al.* (2007) show the protective performance of a specimen with sharp edge coated by a Ferro Magnetic Paint (FMP) system is higher than or equivalent to that with edge preparation coated by ordinary paint system. FMP is an attractive alternative to mechanical grinding of edges. Osawa *et al.* (2007) also point out the protective performance of a top coat applied on a weld bead with blowholes dressed out by 100% solid epoxy/polyamide putty is better than or equivalent to repair welding for dressing blowholes. This proposed method is an effective alternative for blowhole repair.

Tanaka *et al.* (2007) carried out continuous immersion tests in seawater using working stress and plastic strain on corrosion rate, and considered that grooving corrosion on welded joints should grow by galvanic and stress corrosion. Matsushita *et al.* (2007) also investigated the effect of grooving corrosion in way of fillet welded joints on ultimate strength of hold frames of bulk carriers using elasto-plastic FE-analysis. They concluded that the ultimate strength of hold frames subject to lateral pressures is affected by the thickness loss of web plates by general corrosion rather than local grooving corrosion at fillet welded joints between web and side shell plates. In addition, Nakai *et al.* (2007) presented the corrosion pattern observed in structural members with tar epoxy coating and other coating systems of cargo hold of bulk carriers, and concluded applying tar epoxy coating is a very effective measure against deterioration for structural members due to corrosion. Large unevenness by pitting corrosion on structural members make evaluation of residual thickness and/or strength difficult.

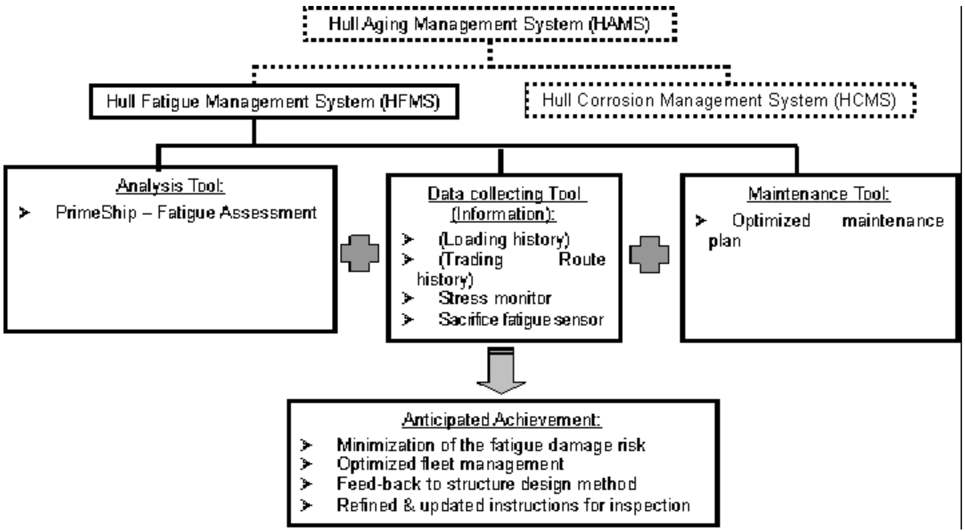


Figure 4.1: Schematic diagram of Hull Fatigue Management System (HFMS)

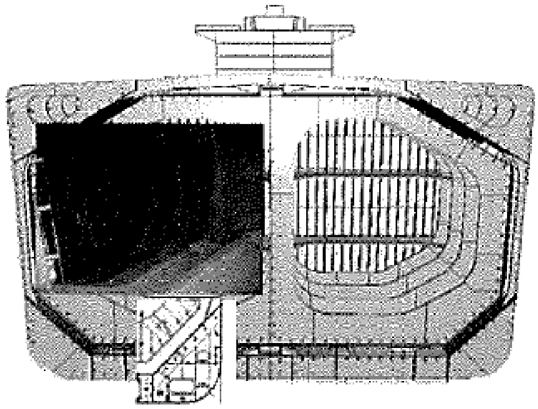


Figure 4.2: Combined 3d graphics, photo and drawings enhance understanding of structural configuration

5. MULTI-CRITERIA AND MULTI-STAKEHOLDER OPTIMISATION

Ten or fifteen years ago, standard available optimisation tools would focus on a single and limited aspect (e.g shape, scantlings, propeller, ultimate strength, etc.) and a single objective would be targeted (weight, resistance, cavitation, etc.). Nowadays optimisation tools tend to adopt a more generic approach and coupled with the fact that they have also become much more reliable this has made them more likely to be part of the standard design tool set that each designer uses on a day to day basis. However, before their universal adoption a number of additional improvements are still required, for instance:

- Polyvalent tools are required for Multidisciplinary Design Optimisation (MDO). These tools should be capable of handling various design aspects such as: hull form, hydrodynamics and resistance; propeller, noise and cavitation; scantling, weight and cost; GA and safety; ultimate strength and crashworthiness; maintenance and life cycle cost. The main challenge is to definitively integrate the production and exploitation aspects (design for production, construction cost and live cycle cost).
- During Multi-Criteria Decision Making (MCDM) it is necessary to seek the optimum design considering various objective functions (criteria).
- Multi-Stakeholders Design (MSD): Since various stakeholders are involved in the design of a ship, optimisation tool must be able to balance the different interests and requirements.

In the previous ISSC 2006 report (Table 2, p.539) committee IV.1 reviewed various formulations and models of Decision Support Problems (DSP) for ship structures and various synthesis models for structural optimisation were identified. Since that time a FP6-European research project dedicated to these aspects was launched and the current IV.2 ISSC committee thus considers it is relevant to extensively present the progress achieved in the framework of this project: IMPROVE (http://www.improve-project.eu/), Rigo *et al*. (2008). The committee thanks the IMPROVE consortium for their permission to release information as their deliverables will not be accessible for most of the readers. For this reason extensive reporting is performed in this report.

5.1 The IMPROVE Project

The IMPROVE project (2006-2009) aims to deliver an integrated decision support system for a methodological assessment of ship design to provide a rational basis for making decisions pertaining to the design, production and operation of three new ship generations. Such support is proposed to facilitate more informed decision making which, in turn, will contribute to reducing the life-cycle costs and improving the performance of those ship generations considered.

The IMPROVE project aims to define the design problem for a series of new generation of ships, by applying the novel Multi-Stakeholder Design (MSD) approach. To this end, the project has identified the design criteria and design parameters based on the requirements of the major stakeholders: the shipyards and ship owners. Multi-objective optimisation was selected over optimisation of ship owner's profit (for instance using a Net Present Value model - NPV) as the IMPROVE project is focusing on structural scantlings and there is insufficient data available to the project to assess the NPV.

The specific objectives of the project are summarised in the following points:

- Creation of integrated optimisation tools that allow multi-criteria and multi-stakeholder optimisation (MCDM, MSD);
- Identification of the design criteria specified by the design stakeholders, the objectives and constraints, and the description of the design parameters (design variables, fixed tactical and technical constants) to allow for the application of automated structural design and optimisation;
- Creation of modules to assess the design criteria and parameters selected by the stakeholders. Design criteria include ship production and ship operation aspects, including life cycle cost;
- Specification of the fundamental reasoning behind the Multi-Stakeholder Design (MSD), and introduction of its basic concepts, especially the concept of competitive optimum.

The project has identified the required tools and modules for both analysis and synthesis in design, which satisfy the identified design objectives and constraints within the considered design scenarios (Table 1).

In addition to the above, the long-term goal is to improve design methodology by concentrating effort on advanced synthesis skills rather than improving multiple complex analyses. The structural design integrates various technical and non-technical activities, namely structure, performance, operational aspects, production, and safety. Otherwise, without doing this it is perfectly possible to define a ship design which is difficult to produce, requires high amounts of material or labour, contains design flaws, or is not cost-effective in maintenance and operation. Additionally, ships should be robust (safe), with high performance in cost and customer requirements criteria.

5.2 Multi-Criteria Decision Making

Ship design entails the achievement of several different objectives, which are often conflicting and non-commensurable, such as improving performance and increasing cargo capacity (see Figure 5.2 (left)). This makes ship design process suitable for optimisation by using multiple objective methods, which yield a family of non-dominated solutions called a Pareto-optimal set. The concept of non-dominance refers to the solutions for which no objective can be improved without worsening at least one of the other objectives. Thus, the non-dominated solutions, referred to as Pareto-optimal design alternatives (PODA), are superior to the others with respect to all objectives, but comparatively good among themselves (Olcer 2006).

From a practical point of view the ship owner needs only one solution, no matter whether the associated optimisation problem is single objective or multiple objective. In the case of multiple objective optimisation, the stakeholders and their experts have a dilemma. Which of these optimal solutions must one choose? With all of these trade-off solutions in mind, can one say which solution is the best with respect to all objectives? The irony is that none of these trade-off solutions is the best with respect to all objectives. The reason lies in the fact that no PODA from the Pareto-optimal set will satisfy all objectives (decreasing cost and increasing performance) or will look better than any other PODA from the Pareto-optimal set. Thus, in problems with more than one conflicting objective, there is no single optimum solution, rather. there exists a number of solutions which are all optimal. Without any further information, no PODA from the Pareto-optimal set can be said to be better than any other. Since a number of PODA are optimal, many PODA are relevant (trade-off or conflicting).

Once PODA lying on the Pareto-optimal set, which are potentially preferred by the experts, are found, higher-level decision-making is usually required to choose one of them for implementation (see Figure 5.2). The choice of one solution over the other requires additional knowledge, e.g. ship owner’s preferences. These preferences can be elicited a posteriori in higher-level decision-making process. Multiple-Criteria Decision Making (MCDM) techniques are generally employed in posterior evaluation of PODA to choose the best one.

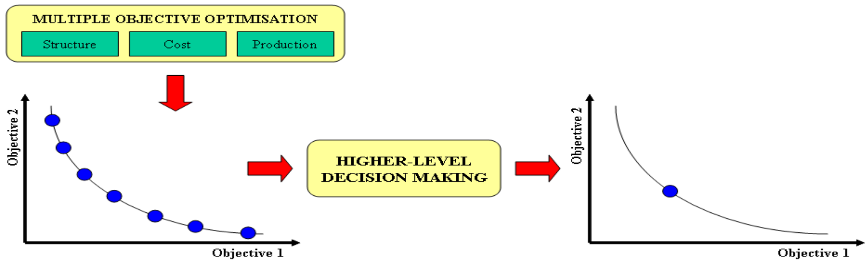


Figure 5.2: Higher-level decision making in the IMPROVE framework (Olcer, 2008)

The MCDM is the technique used to determine the best alternative with the highest degree of desirability with respect to all relevant attributes from a finite number of alternatives when faced with conflicting objectives. The MCDM problems share the following common characteristics:

1. Alternatives: A finite number of alternatives, which are mutually exclusive, from several to thousands, are to be screened, selected and ranked.
2. Attributes: Each alternative is characterised by a number of attributes and these attributes should provide a means of evaluating their levels. In IMPROVE, the attributes are construction cost, maintenance and exploitation cost, production related aspects and some other subjective attributes.
3. Decision matrix: An MCDM problem can be concisely expressed in a matrix format called a decision matrix. This decision matrix is constructed with information on the values of the attributes for the various alternatives.
4. Incommensurable units: Each attribute has a different unit of measurement. For example in a ship selection case, fuel consumption is expressed in tons per mile, cargo capacity is expressed by m3 (or tons), and cost is indicated by € or $, but safety may be indicated in a non-numerical way.
5. Attribute weightings: Almost all MCDM problems require information regarding the relative importance of each attribute. The relative importance is usually given by a set of weights Wj (j=1, k), where k is the number of attributes and weights are generally normalised such that their total sum is equal to one. The assignment of weights plays a key role in the MCDM process.

There are two main types of attributes in MCDM problem (Olcer *et al*., 2005), namely 'subjective' and 'objective' attributes. If a performance rating for an alternative with respect to an attribute is crisp (or deterministic), this kind of attribute is called an "objective attribute". When experts' opinions for an alternative with respect to an attribute are subjective assessments, then this attribute is called a "subjective attribute". Subjective and objective attributes can also be divided into two classes. The first class is of 'cost' (or 'input') nature (the larger the attribute, the lesser preference). The second class is of 'benefit' (or 'output') nature (the larger the attribute, the greater preference).

5.3 Meta-Modelling of Criteria Functions and Subspaces

Typically, the analysis of the components of such systems, such as life cycle cost, is expensive thus hindering the search for optimal designs. The high computational expense of such analyses limits, or even prohibits, the use of such codes in engineering design and multidisciplinary design optimisation (MDO). Consequently, approximation methods such as design of experiments combined with response surface models are commonly used in engineering design to minimise the computational expense of running such analyses and simulations.

The basic approach is to construct a simplified mathematical approximation (response surface) of the computationally expensive simulation and analysis code, which is then used in place of the original code to facilitate multidisciplinary design optimisation, design space exploration and reliability analysis etc. Since the approximation model acts as a surrogate for the original code, it is often referred to be a surrogate model, surrogate approximation, approximation model, or metamodel (i.e. a "model of a model"). A variety of approximation models exist including polynomial response surfaces, kriging models, radial basis functions, neural networks and multivariate adaptive regression splines.

In choosing an approximate method for a specific application, the implementation effort is weighted against the performance of the algorithms as reflected in their computational efficiency and accuracy and better approximations are often achieved at the expense of more computational effort. In various applications the different levels of analysis range from inexpensive and inaccurate to costly and accurate. Within the various approaches to define this approximate model, Schmitz (2008) proposes neural networks as a response surface method. A synthesis level multi-disciplinary design and optimisation (MDO) method has been developed for multi-hull ships (Hefazi 2008). This method uses multi-objective optimisation methods, in its broad scope, integrating powering, stability, seakeeping, hull forms definition, cost and payload capacity into a single design tool (Besnard 2007). More specifically, neural networks that have undergone training based on sets of CFD data can be used for the estimation of powering and seakeeping through the optimisation loop.

Generally, the MDO design system (Fig. 5.3) consists of the synthesis design method summarised in the following bullet points:

- Hull form definition and optimisation
- Sub-system optimisation
- Seakeeping
- Structural design optimisation
- General and cargo arrangement design and optimisation
- Propulsion machinery sub-systems design
- Local sub-systems such as: outfit, electrics and handling systems

Seakeeping, power, and payload are primary functional relationships, which depending on the stage of the design, are analyzed at various degrees of fidelity.

Two major challenges of MDO design system are:

- MDO is required to formulate a design in which there are several criteria or design objectives, some of which are conflicting.
- Subsystem performance evaluations (such as powering, seakeeping, crashworthiness, etc) are often very complex and (computationally) intensive. Direct evaluation of these performances as part of the optimisation process, may make the MDO method overly costly and thus out of reach of most practical design problems.

To overcome these limitations, Hefazi *et al*. (2008a and b) propose the use of advanced multi-objective optimisation methods such as Neighbourhood Cultivation Genetic Algorithm (NCGA) for optimisation. Unlike traditional design spiral approaches, multi-objective optimisation keeps various objectives separate and concurrent in order to find the best possible design, which satisfies the (opposing) objectives and constraints. To address the subsystem performance evaluation challenge, artificial neural networks are trained on the basis of model tests or computed data bases and are used in the optimisation process to evaluate various subsystem performances. This innovative approach replaces the use of highly idealized or empirical methods for evaluation of subsystem performances (such as powering, seakeeping, etc) during the optimisation process.

The overall MDO process is schematically shown in Fig. 5.3. It consists of various "models" to evaluate powering, cost, stability, seakeeping, structural loads, etc. The outcomes of these models are then used by a multi-objective optimisation method to perform the optimisation.

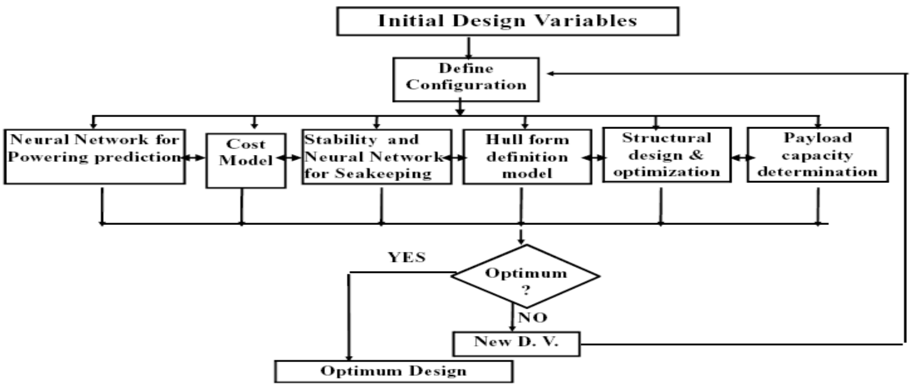


Fig. 5.3: Multi-disciplinary design and optimisation process - MDO (Hefazi *et al*., 2008)

5.4 Engineering Design as a Decision-Making Process

A complex engineering product, such as a ship, is a system possessing various functional characteristics. If it can be parameterized, its development may be formalized as a decision making process. Decisions are based on ***decision parameters*** x and comprise a decision maker making a choice on the value of x to attain some positive outcome. Typical parameters for a ship include: main dimensions, hull form, internal subdivision and spatial topology, geometry of stiffening and scantlings of structural elements. A design process is then a mere sum of sequential and parallel decisions on a vector of decision variables **x** by one or more designers, and a value of vector x will be chosen such to maximise the system's performance. Then, with respect to design, decision parameters can be also addressed as design parameters. These are system descriptors, and can be quasi-statically separated into ***design variables***, those that are temporarily open for change and variation, and into **exogenous parameters**, or tactical and technical constants, which are temporarily fixed.

The performance of a system can be further formalized through the definition of an attribute. An ***attribute*** is a function of **x**, a quality measure which dedicatedly enables comparison of one product to another, and returns information to a designer as to whether the chosen value for **x** is satisfactory or not. A single system may be described with more than one attribute and a system can also be designed with respect to strict maximization or minimization of a particular attribute. In this case instead of attributes we speak of ***objectives***. An attribute might be also targeted for a certain level or a ***goal***. Cost, weight and safety measures are standard ship attributes/objectives. Some attributes may be compounded by others, and those that are considered important may be also called the ***Key Performance Indicators – KPI.*** These also reflect on the generic comparison of the ship in design, enabling distinction of its performance over the whole market range. Some examples of KPI are lead time in production, fatigue life, vibration and noise levels. Typical goals on the other hand might be a fatigue life of 40 years.

Besides setting a particular aspiration levels for the system's KPI and attributes, the designer also considers their minimal or maximally acceptable levels. These then become design ***constraints***. They are typically defined as lower and upper bounds of design variables, as failure functions or with technological limits. Constraints limit the ***design space*** of acceptable or feasible systems design alternatives, but they also represent the necessary values of some of the design goals. In the structural design, the optimal cost/weight design will typically lie on the boundary of the feasible region that is determined directly by the structural constraints.

The design and attribute spaces are fundamental in understanding the limitations, interrelations and the trade-offs between the multiple parameters and the attributes, objectives, goals and constraints. All the mathematics of decision making, but also of optimisation as an automated search procedure for the best performing alternatives is conducted within these two spaces. Jointly, the attributes, objectives, goals and constraints are addressed as ***design criteria***. Thus, a criterion, if well defined, is a formal and mathematical representation of part of the design environment. Many criteria will then formalize a complete design environment, design scenario and mission along with its drivers and outcomes. Engineering design facing multiple criteria is then approachable through the methodology of ***Multiple Criteria Decision Making (MCDM).***

During the life-cycle of a complex engineering system in business-to-business markets there will be a number of formal parties who will be both involved and exerting strong influence. The influence of these parties is much stronger than that of consumers for mass business-to-consumer products. This can be argued due to involved higher monetary values of the product, strong customization, one-of-production and longer product life cycle. For instance, for ships these parties are regularly shipyards as sellers and ship owners as buyers. Additionally to them, the influence is exerted by Classification societies as independent control bodies, cargo owners and consumers, or passengers, insurers, flag states, international organizations protecting lives, environment and goods at sea such as IMO, etc. According to Stakeholder theory of management science these parties are then stakeholders, and their interests need to be addressed.

In addition to these stakeholders the design of engineering systems also involves multiple experts due to their multi-disciplinary nature. Therefore, a system will be designed as a group effort. These designers and experts jointly contribute to the effort, sharing responsibility and duties, but similarly to the already indicated stakeholders, they do not necessarily exert uniform priorities on the importance of the system's characteristics. Also, the importance of their judgement and decision-making will differ (Olcer and Odabasi, 2005).

MCDM (Multi Criteria Decision Making) provides a good background for decision making in the environment of multiple stakeholders, especially if we extend the definition of a criterion onto stakeholder's satisfaction.

5.5 Multi-Stakeholder Design: Theoretical Background

Stakeholders tend to look upon a certain design alternative from diverse perspectives, and thus assess the importance of its design attributes differently. The approach considered by IMPROVE aims to assist in situations where it is necessary to adopt customer preferences in design, and also satisfy them as much as possible alongside that of all other stakeholders.

Marketing literature suggest that value should be studied from relational perspective. This is particularly true for most of the industrial and service business where the buyer and seller are usually both engaged in a long-term relationship. Ship design incorporates both aspects, as it is a professional service in an industrial business context. The shipyard offers a design service prior to building and selling the ship to the ship-owner, and the process may take from at least one year to three or more years in case of complex ships. It is thus appropriate to adopt a relational approach to study the value of a ship (Wang 2008).

Classical approaches separate this first into problems per stakeholder then further into a series of multi-attribute (MA) decision-making, or optimisation problems, which are solved independently. However this approach does not often lead to globally satisfactory solutions if the system's attributes and parameters are both dynamic and interdependent. This specific problem of interdependency was recognized, and advances made through the application of multi-criteria decision-making theories, namely the concepts of Game theory of von Neumann and Morgenstern and through the generation of joint group preferences (See and Lewis, 2006). However, this methodology omits the wider axiomatic characterization from the stakeholders' perspective, and which is crucial in determining the fair distribution of benefits and share of risks amongst stakeholders. To understand the stakeholders, their relationships and valuation of ship design, their requirements and sufficiently model their preferences, it is very important to carefully study the business reasoning, and their business drivers. The MSD approach considered in IMPROVE follows the basic concepts defined in Klanac *et al*. (2007), and was used as the backing argument for the decision to formulate the design problems of the IMPROVE's products as the multi-stakeholder problem.

In IMPROVE, the selection of preferred design alternatives by different stakeholders, exhibiting measurable and verifiable indicators, defined as "Key Performance Indicators" (KPI), are shown in Table 1. This Table was established based on the data collected for three ships (LNG, ROPAX and Chemical Tanker). It gives the design objectives, the KPI, the design variables and few relevant tools to assess these functions (non-exhaustive list). It is expected that the generated design alternatives will show some of the following potential improvements:

- Increase in ship carrying capacity.
- Decrease of steel cost; decrease of production cost corresponding to standard production.
- Increase in safety measures via the rational distribution of material and a priori avoidance of the design solutions prone to multimodal failure.
- Improved operational performance and efficiency, including a benefit on maintenance costs for structure (painting, corrosion, plate/stiffener replacement induced by fatigue, etc.) and machinery, and reduced fuel consumption.

5.6 Fundamental Design Support Systems

IMPROVE did not develop new mathematical optimisation methods but instead focused on an existing Design Support Systems (DSS) based approach to the design of ship structures and aims for more efficient use of these available optimisation packages and their integration in the design procedure. IMPROVE focuses on the methodology/procedure that a designer and shipyard should follow to improve efficiency in designing, scheduling and production of ships. IMPROVE also introduces certain optimisation techniques that can individually improve the overall design procedure. This methodology should be used to improve the link between design, scheduling and production, with close link to the global cost. Indeed, it is only through such integration that specific optimisation tools can be proposed to shipyards to improve their global competitiveness.

There are four DSS considered by IMPROVE, these are summarised below:

- LBR5
  LBR5 is an integrated software package used to perform optimisation of ship structures at the conceptual design stage in terms of cost, weight and stiffness. [Richir *et al.* , (2007), Toderan *et al.* , (2008)]. LBR5 is linked with the MARS (Bureau Veritas) tool, from which geometry and loads can be automatically imported to establish the LBR5 models.

- MAESTRO
  This software combines: rapid ship-oriented structural modelling; large scale global and fine mesh FE analysis (quasi-static and free vibrations); structural failure evaluation; scantlings and topology optimisation [Zanic *et al.* , (2007a), Dundara *et al.* (2008)] in forming an integrated software environment for the preliminary design stage.

- OCTOPUS DSS
  This software is used for the concept design phase (Zanic *et al.* , 2006, 2007b) contains modules for simplified FEM response calculations (8-node macroelements), ultimate strength and system reliability evaluations combined with a set of optimisation solvers. Seamless transfer to MAESTRO preliminary design DSS is assured.

- CONSTRUCT
  This is a modular tool for structural assessment and optimisation of ship structures in the early design stage of ships (Klanac *et al.* , 2008). It applies the Coupled Beams method (Naar *et al.* , 2005) to rapidly evaluate the structural response and the fundamental failure criteria.

5.7 Enhancement for Multidisciplinary Links in Synthesis Models

The DSS-based approach has as its objectives to enhance:

– Linking of “design” with “maintenance and operational requirements”, which may differ from the standard shipyard approach;
– Linking of “design procedure” with “production” through an iterative

optimisation approach;
- Linking of “design procedure” with “cost assessment” and therefore drive the design to a least-cost design (or a least weight if preferred);
- Linking of “production” with “simulation” and therefore drive the design to a higher labour efficiency along with better usage of man-power and production facilities.

Enhancement of present state-of-art products/procedures using new improved synthesis models includes:

- Demonstration of the feasibility of increasing shipyard competitiveness by introducing multi-disciplinary optimisation tools
- Demonstration of an acceleration of the design procedure
- Propose new alternatives to designs. Scantling, shape and topology optimisations can lead to new solutions that may or may not fit with standards and Class Rules. Such revised designs have to be considered by the designers as opportunities to “reconsider the problem, its standards and habitudes”, to think about the feasibility of alternative solutions, etc. At the end of the day, the designer has still to decide, based on his experience, if there is a new way to explore (or not).
- Test newly developed design approach on three applications (RoPax, LNG carrier, chemical tanker) by associating a shipyard, a classification society, a ship owner and a university.
- Enhanced modelling of advanced structural problems in the early-design optimisation tools (e.g. crashworthy hull structure, ultimate strength, vibration and fatigue limit state in structures).

A key to successful employment of such integrated design methods is of course an acceptable level of specialized tool development, the topic of the next chapter.

Table I
List of Design objectives and List of Design Variables (part 1)

		DESIGN OBJECTIVES and Sub-Objectives	QUALITY MEASURES including the KPIs KPI = Key Performance Indicator	DESIGN VARIABLES	TOOLS
SHIP (NAVAL ARCHITECTURE)	Max volume	Increase carrying capacity (lane meters)	- Additional trailer lane meters on tank top, - Total lane meters, - Decreased length of the engine room	General Arrangement (GA), length of the engine room, hull form, required power output, type, size, number and configuration of main engines, boilers and other parts of machinery,	Concept design, tools for the design of machinery systems, reduction of power requirements (reduction of resistance and increase of efficiency of the systems),
		Increase carrying capacity by: → reducing the steel mass; → reducing the void spaces; → reducing the internal subdivisions; → maximising cargo volume per dimensions	- Steel mass, - Volume of void spaces, - Number and volume of ballast tanks, - Cargo volume per ship dimensions	- GA, scantlings, - Ratio of mild steel vs. high tensile steel or vs. DUPLEX steel (for CT), - Stability requirements, loading conditions, lengths of fore, and aft peaks, bulkheads type and arrangement, volume of ballast tanks,	- Concept design tools, - Optimisation tools (dedicated to conceptual and basic design stages) - Machinery design tools
		Determine the optimum size for chemical tankers	- Max utilisation of cargo part volume - Lightship weight (mass of steel, outfit) - Possible future conversion allowance	Cargo capacities, types of cargo, area of navigation	- Concept design tools : - Economical analysis.
	Flex.	Achieve load carrying flexibility		RoPax: deck loading, tween deck clearances, number of cabins, no of aircraft seats, CT: number and position of cargo tanks	- Concept design tools,
	Hydrodynamics	Improve the seakeeping performance for the Mediterranean Sea	- Speed loss in waves, - Number of deck wetness, - Number of propeller racings,	Hull form, ship mass distribution,	- Seakeeping analysis software
		Improve the manoeuvrability of the ship	- Turning ability index	Hull form, main particulars, type and number of propulsors, bow thrusters and rudders,	- Manoeuvrability analysis software - Towing tank trials
		Reduce the hydrodynamic resistance	- Power requirements, - Trial speed	Hull form, main particulars,	- CFD analysis, towing tank trials, - Seakeeping concept design tool
		Maximise propulsion efficiency/Minimise the fuel consumption	- FO consumption	Hull form, propulsion system	- Open water test, self propulsion tank tests,

CT = Chemical Tanker

Table I
List of Design objectives and List of Design Variables (part 2)

		DESIGN OBJECTIVES and Sub-Objectives	QUALITY MEASURES including the KPIs (Key Performance Indicators)	DESIGN VARIABLES	TOOLS
SHIP (NAVAL ARCHITECTURE)	Economy	Minimise required freight rate	- Required Freight Rate	Economy parameters,	Production Simulation Tools
		Maximise robustness of the required freight rate	- SN ratio of RFR	Economy parameters,	Production Simulation Tools
		Minimise cost of the main engine and machinery	- Main engine cost - Machinery cost	Required power output, type, size, number and configuration of main engines, boilers and other parts of machinery, efficiency of systems,	Concept design, design of machinery systems, reduction of power (reduction of resistance and increase of efficiency of the systems),
	Safety	Maximise ship safety	- Subdivision index, - Redundancy index, - Evacuation ability index - Structural safety index (system and component)	GA, scantlings, systems and equipment, freeboard height, number and positions of bulkheads, number of passengers, internal layout, number of independent propellers, engines and engine rooms,	Structural analysis, evacuation ability simulations, damage stability calculations,
		Design for redundancy and simplicity of systems	- Number of independent propellers, - No of engines and no. of engine rooms,	Number of independent propellers, engines, engine rooms, etc.,	
		Maximise reliability of the ship systems		Scantlings, detail design, GA, equipment,	Structural analysis and fatigue assessment , reliability analysis,
	Specific	Maximise comfort: → minimise vibrations → minimise noise levels	- Vibration levels (displ., velocity, accel.) - Noise levels (dB) For RO-PAX: - Size of cabins/public spaces per pax, - No. of crew members per pax, - Pax service facilities, - Motion Sickness Incidences (MSI),	Size of cabins and public spaces per passenger, number of crew members per passenger, passenger service facilities, vibration levels (GA, scantlings, shape of the stern part, vibration reduction devices), noise levels (insulation, materials, noise sources),	Concept design tools, Software for vibration analysis, Software for seakeeping analysis.
		Achieve flexibility in regard to possible conversion due to new rules or comfort standards		Size of cabins and public spaces per passenger, number of crew members per passenger, passenger service facilities, seakeeping performance, vibration levels (GA, scantlings, shape of the stern part, vibration reduction devices), noise levels (insulation,)	Concept design Tools
		Reduce draft in ballast condition		Size, number and type of propellers, manifold position,	Concept design Tools

Table I
List of Design objectives and List of Design Variables (part 3)

	DESIGN OBJECTIVES and Sub-Objectives	**QUALITY MEASURES including the KPIs (KPI = Key Performance Indicator)**	**DESIGN VARIABLES**	**TOOLS**
STRUCTURE	- All Ships: Minimise the steel mass; -Chemical Tanker(CT):minimise DUPLEX steel mass; - RoPax: minimise mass of freeboard deck ;	- Steel mass = additional deadweight, - Use of Mild Steel (% of total mass), - Painted surface, - DUPLEX-steel mass (for CT), - Mass of freeboard deck (for RO-PAX), - Longitudinal spacing (for RO-PAX)	GA, scantlings, ratio of mild steel vs. high tensile steel vs. DUPLEX steel (for CT), bulkheads type (CT), direction and dimensions of bulkhead corrugations (CT), framing systems of decks and bulkheads, still water bending moment (CT)	Concept design tools, optimisation tools (dedicated to conceptual and basic design stages), still water bending moment distribution, analytical methods for structural analysis
	Maximise structural safety w.r.t. - Extreme loads - Fatigue life (constraint)	Global deterministic safety measures: - Max. Ul. Bend. Mom. in sagging (Mult,sagg) Max. Ul. Bend. Mom. in hogging (Mult,hogg) - Max. racking moment for RO-PAX (Mrack) Global reliability measures: - System failure probability in long. strength - System failure probability in racking (ROPAX) Local deterministic measures: - Fatigue life of structural details (No of cycles before fracture), - Panel ultimate strength measure, - Principal member ult. strength measure. Local probabilistic measures and robustness measures: - Probability of fatigue failure of structural details. - Probability of panel failure in regard to all relevant failure modes, - Probability of frame/girder failure in regard to all relevant failure modes. Panel and frame/girder robustness measure (SN ratio)	Scantlings, structural details, loads, GA, type of structural material, quality of fabrication and welding,	Accurate load estimation (especially of the wave loads with e.g. lifetime weighted sea method or CFD analysis), Structural evaluation tools:FEA, fatigue analysis, reliability analysis: - Ultimate Bending Moment - Smith method, - Mrack - incremental FEM analysis, - Fatigue Live: Weibull, Joint Tanker Rules, - EVAL (Panel, Principal member) - CALREL (SORM) - SN ratio - Fractional Factorial Experiments (FFE)
	Minimise the height of deck transverses	Ship height, CG Vertical position	Loads, position and number of supporting members (pillars) → effective spans of deck transverses, scantlings	Optimisation tools (dedicated to conceptual and basic design stages)

Table I
List of Design objectives and List of Design Variables (part 4)

	DESIGN OBJECTIVES and Sub-Objectives	QUALITY MEASURES including the KPIs (Key Performance Indicators)	DESIGN VARIABLES	TOOLS
PRODUCTION	Minimise production costs (compound objective)	Production cost = material cost [€] + labor cost [€] (steel production per unit of time (welding, bending, straightening,…) [t/h], compensated steel throughput per year [CGT/year], cost of steel work per mass [€/t], building blocks number [units], lead time/cost [TLH in hours or €] in dry dock (or slipway) and in all shops, key resource use [TS, in days] - time first part into resource until last part, degree of pre-fabrication = TLH / TS [%], usage of space per CGT [m²/CGT], degree of outsourcing - yard hours against subcontractor hours) + overhead costs [€]	Scantlings, complexity of parts, organization of the production process, materials, technologies needed, shops used, shipyard transportation equipment and available technical capabilities (like the capacity of panel line, sub-assembly and assembly shops, etc.), quality of fabrication in the steel mill, level of attention during the transportation and storage actions, number and size of curved parts	Production simulation tools, concept design, structural design tools,
	Minimise additional construction cost due to a double-bottom height higher than standard width of steel plate		- Double-bottom height	
OPERATION, MAINTENANCE AND REPAIR	Minimise lifecycle cost of the ship (compound objective - selection from Pareto frontier)	Lifecycle cost = Initial cost (production cost + other costs) + Cost of operation (preventive maintenance cost, corrective maintenance cost (repair cost), fuel, crew and provisions, turnaround time in port and port charges, time out of service bond interest)		
	Minimise maintenance costs	- Preventive maintenance costs (including inspection costs), - Corrective maintenance costs (repair costs)	Scantlings, quality of fabrication, design of systems and quality of components, availability of components for inspection,	
	Maximise reliability of the ship's machinery			
	Maximise robustness of the propulsion system			

6. RECENT DESIGN TOOL DEVELOPMENTS

The Particle Swarm Optimisation (PSO) algorithm, mentioned previously, has been successfully used in single-objective optimisation problems since 1995. However, in multi-objective optimisation, because PSO focus on cooperation, it may not put enough pressure to push the solution space to a Pareto surface. In 1999 developers proposed the first extension of the PSO strategy for solving multi-objective problems, a great deal of interest has been shown in multi-objective optimisation and many different approaches/techniques have been presented in the literature.

Cui *et al*. (2008) introduces a novel hybrid co-evolution based multi-objective particle swarm optimisation (HCPSO). The HCPSO combine co-evolution, game theory and extremum analysis to develop an effective optimisation approach. It performs remarkably well in a multi-agent system. They present application of multi-objective particle swarm optimisation on hull subdivision design of a Ro-Ro passenger vessel. Indeed the internal hull subdivision in ship design is important for damage stability, survivability and cargo capacity performance, particularly for RORO passenger vessels, which have conform to SOLAS standards including SOLAS 90 (Stockholm Agreement). The ship design needs to be optimized to achieve these high safety standards and cost effectiveness.

Thus we repeatedly see a clear connection between optimum design and various analytical tools ranging from product performance assessment to cost modelling. Also, designers aim at having computer based design tools capable of fulfilling several requirements, which may also slightly change as a function of the kind of ships to be designed and built. If the vessel is a conventional merchant one, as a container ship, a bulk carrier or a tanker, it is possible to define a certain number of parameters that could be managed by dedicated software. Some yards have developed their own macros or manager applications for the semi-automatic definition of ship structures: for instance, both in Tribon and in NAPA system a proper customization (tailored on yard standards) can allow the designers to produce 3D structural models in a very short time.

Such models are the basis for the generation of FEM meshes and for the extraction of all the conventional classification drawings required by the Classification Societies. In that case the design phase is unbalanced towards production, because the structural solutions are already well known and the variations from the standard are often limited in number and contents, so that the design tool must mainly assist the production phase, focusing especially on structural details and on the graphical representation of workshop documents. A good deal of shipbuilding companies uses Tribon system, which seems to adequately support this phase.

For cruise ships, ferries, naval vessels, mega-yachts and non-conventional ships, the structural designer has to face the challenge of creating tailored structures, the “steel dress” to suit different and complex general arrangement layouts.

6.1 CAD/CAE Systems

The growing presence of Architectural-Design external shapes in both cruise ships and mega-yachts has created a new generation of "fashion plates", leading to, for example, different stiffening solutions. In that case the flexibility of the design tool is the main need from the designer's point of view. Pure graphic tools, like the most widespread CAD systems (AutoCAD, Microstation, etc.) are widely used to finalize the classifications drawings. Other software codes, like NAPA and NAPASteel, provide the opportunity to easily write out customized macros and generate a topological and parametric structural model, which is extremely useful since the concept design phase.

For this type of design, it is very important to check the feasibility of some interior or exterior-designer proposals (for instance, large and shaped openings on decks, sides, external shell, etc.) or to perform a weight-oriented calculation that requires a quick overall view of the ship structure without entering in construction details. In prototype design, the structure must first satisfy strength requirements, but also represent the boundary scenario for machinery arrangement and outfitting layout. Moreover, it must be designed in a feasible way considering yard facilities and industrial capabilities in general.

From a pure scantling approach, it is important that the geometry defined in one system can be exported into 2D Sections or 3D Beam or FEM codes: some well known 2D Section analyzers can import DXF curves, while others can benefit from the close connection (i.e. NAPASteel-ABS for JBP project) between a structural modeler and a strength analyzer. Some of the software codes for the modeling phase offer the option to create an internal mesh, which can be exported to FEM processors/solvers like Patran/NASTRAN or ANSYS, transferring all or part of the element properties, previously defined, in various formats (neutral, bdf, etc.).

The challenge of designing ships, having extremely technical diverging needs, such as mega yachts with L > 140 m and speed exceeding 35 kn, while keeping a luxury comfort level, implies that FEM simulations must be performed in the pre-contract phase, when the geometrical elements are still not fixed and many changes could occur. A good design tool should allow producing one single structural model, which can be used for the extraction of classification drawing as well as for the generation of a FEM model to be processed by the most common dedicated codes (like Patran/NASTRAN and Ansys).

The designer must have a high-level knowledge of both systems to carry out the structural model in such a way that the derived FEM mesh is easy to run (which means including all possible time-saving tricks). Compared to the past, this new generation of FEM export possibilities allows the designer to use FEM as a real "design" tool to explore the structural behavior of the ship instead of using FEM as a confirmation of semi-known solutions or just for details once a complete set of steel drawings have been carried out. For naval applications, further FEM simulations are performed taking account of the non-linear properties of hull materials and/or the non-linear characteristics of specific loading conditions (as in case of shock, blast or other military threats).

Dumez *et al.* (2008) have developed an ultra fast 3D ship modelling and grid generation tool based on four cornerstones: parametric modeller, generativity, granularity, and propagation. These four elements enable the creation of 3D CAD models of complete ships in a few days. The model obtained is topologically connected, allowing automatic updates of the definition by changing some parameters, and to readily extract a structural mesh of the whole ship or its associated compartment plans.

For the same purpose Forrest (2008) introduced a novel hullform generation technique for the Paramarine ship and submarine design system. He discussed the requirements that shaped the development of the technique in terms of the user interface, the underlying mathematical methods, the need to function in a parametric environment, and the importance of compatibility with the design system's extant solid modeller. Such requirements were assembled over many years using literature searches, application prototypes and user consultations. General features of the design solution are described. The user interface is a key component of the system and enables a patchwise hull to be developed rapidly and intuitively. Surface objects are built up from curves and define a hullform in terms of a series of patches. The curves are associative and use high-level parametric definitions in order to achieve the user's requirements.

In global FE ship analysis there are two laborious steps: Building the global finite element model and assessing the structure based on the finite element results. In general the assessment cannot be performed only using the global finite element model and results - additional information about structural details or loads are also needed when derived physical quantities like buckling usage factors should be computed. Germanischer Lloyd (Wilken *et al.* 2008) proposes a technical solution and observes different modelling requirements between finite element computation (where idealized structural information is necessary) and derived results assessment (where detailed structural models have to be used) and a way to use 3D CAD data to derive this information.

For a similar purpose the UCL Design Research Centre proposes an Interactive Computer Graphics and Simulation in Preliminary Ship Design. Indeed, Andrews *et al.* (2008) introduces the Design Building Block approach and the Paramarine Surfcon software, which is applied to a range of preliminary ship design studies and investigations.

Brahaug *et al.* (2008) propose a configuration-based process for tender project development. It is specifically targeted towards complex, arrangement-intensive ship types such as offshore support vessels, and it will seek to exploit recent investment in module-based design platforms in the industry. One particular area that is addressed is how to represent the particular design knowledge required for driving this configuration process from a set of customer requirements and KPIs, into a complete tender package comprising a diversity of elements, such as the vessel parametric description, a contract specification, cost calculation, 2D arrangements and 3D visualisation models. It is also discussed how rule based frameworks can be used in an industry context to capture required knowledge, such as company specific product platform rules (the existence, relevance, inferred properties and derived performance of scalable modules), generic ship design rules, and external rules from class societies and authorities.

6.2 Design Tools for Production and Cost

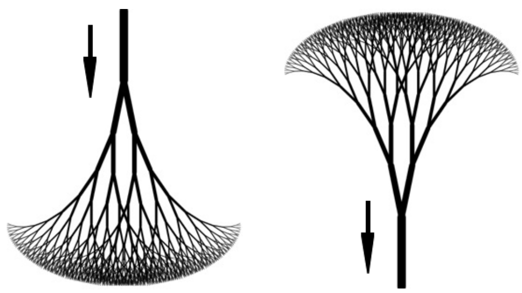
To succeed commercially, the shipyards must be able to accurately assess costs. Cost assessment is necessary for the bidding process, for subcontracting orders, and for trade-off studies. The options for the production cost assessment differ with the level of information required to run the analysis (input data). If less information is needed, the earlier a method can be employed in the design process. If more information is used, the finer differences between design alternatives can be analysed, but the analysis will be performed later in the design process [Bertram *et al.* (2005), Caprace *et al.* (2006)].

The methods for estimating production costs are classified into:

Top-down (macro, cost-down or historical) approaches (empirical, statistical and close form equations etc.), see Figure 6.1(a).

Bottom-up (micro, cost-up or engineering analysis) approaches (direct rational assessment), see Figure 6. 2(b).

More information on bottom up approaches is included in ISSC Committee V.3: Materials and Fabrication Technology.



(a) Top-down (b) Bottom-up

Figure 6.1: Top-down and bottom-up methodology

The top-down approach determines the production cost from global parameters such as the ship type and main dimensions, weight of the hull, the block coefficient, ship area, complexity, etc. The relations between cost and global parameters are found by evaluation of previous ships. Thus, the top-down approach is only applicable if the new design is similar to previous ships. In addition, the cost estimation factors will reflect the past practices and experience. However, this cost evaluation method is appropriate for the early design stage when the data available are small.

Cost reductions resulting from newly adopted and developing shipbuilding technologies and production methods are not reflected in the existing historical based cost estimating techniques. Advanced shipbuilding technologies typically involve a module (product oriented approach) which removes (or reduces) elements from the existing Ship Work Breakdown Structure (SWBS). Thus, even the basic structure of the current approach to ship cost estimating is of questionable relevance for modelling the ship construction processes and cost assessments of the future (Christiansen *et al.*,1992).

Ennis *et al.* (1998) concluded that weight based cost assessment approaches do not reflect improvements that may occur in the production process. For instance, if a new welding technique is used which takes 25% less man-hours per foot of weld no change would be reflected in cost, because there is no change in the weight of the ship. Therefore, if a change in design or production process has no impact on weight, then the cost assessment will not change.

However this approach is often used in a very early design stages as it is very simple to use. Weight is often used as the primary driving factor for cost assessment as it encapsulates the amount of material and to some extent work associated with an item. Weight is an important characteristic to be established very early in the design of any vessel and there are several parametric rules, which can be used to estimate weight based on such minimal information as the main dimensions and the hull form coefficients.

Recent publications on "Cost Estimating" Deschamps *et al.* (2004) refers to a series of systems (tools) used for navy ships: ASSET, ACEIT, UPA, PRICE, and finally the PODAC (Product-oriented Design and Construction) cost model. PODAC [Ennis *et al.* (1998), Keane *et al* (1993), Wade *et al.* (1997)], is a rather sophisticated top-down approach. However, PODAC can be linked to other ship design tools with cost estimating capabilities that operate at more detailed level analysis.

Ross *et al.* (2005) proposes a ship cost assessment method based on weight estimating at the early design stage of the project. According to Ross, weight is the most important attribute upon which initial design cost can be based. Weight can be estimated parametrically early in the design process, and is thus more immediately available than attributes such as weld length and surface area. He implemented a computer aided approach to assess weight and cost to support the initial design process where the key factors are calculated from historical data.

To make most use of the simulation, coupling optimisation with simulation is expected to be far more effective to improve the planning quality as well as to reduce the efforts in production planning and control (Bair *et al*. 2005, Caprace *et al*. 2008).

Another key issue concerns the development of tools for cost assessment (hull production cost – long, medium and short terms; outfitting cost, life cycle cost including maintenance, etc.). To reduce the business risk associated with tendering a very competitive offer, the shipyards must accurately assess their production costs. Cost assessment is necessary for the bidding process, for subcontracting orders, and for trade-off studies. The options for the production cost assessment differ with the level of information required to run the analysis (input data). If less information is needed, the earlier a method can be employed in the design process. If more information is used, the finer differences between design alternatives can be analysed, but the analysis will be performed later in the design process [Bertram *et al*, (2005), Caprace *et al*. (2006), Toderan *et al*, (2007)].

6.3 Design Considerations for Fire and Smoke

The most recent survey on computer models for fire and smoke is available on the internet on the website http://www.firemodelsurvey.com/ and has been updated by Olenick and Carpenter (2003). In this survey the author asked the developer of the most available software to provide information on computer models as the price, the computer hardware needs, some references and a description. These models are divided into two main groups of models: zone models and field models. The main interest of this survey is to provide an overall view of the fire simulation tools available. One can also find the results of the survey dealing with detector response models, egress models and finally, fire endurance models (fire resistance of structures).

Bureau Veritas is involved in different research and commercial projects dealing with fire engineering for ship design and has now developed a complete experience and know-how on different aspects of fire simulation tools, evacuation advanced tools and their trends (Chantelauve, 2004 and Gutierrez, *et al*. , 2008). These tools and their developers address different topics: accuracy, use of simple models, new functionality, simulation speed, user friendliness, access to input parameters and coupling possibilities with other pieces of software.

Today the first question on a fire model is “is it validated” and a clear response will always be hard to provide, since it depends on the application and the objectives. Of course all the models have been developed by serious members of the fire science community which had a validation program and presented a series of validation papers. One should always pay attention to those references and check if the model is used in a way it has been validated for. Good practice for fire simulation using specific software should be given in the user guides and technical guides associated to the software used. Nevertheless, techniques to reach the most valuable results (which would be the optimum between accuracy and energy spent to model) are not written in books and should be learned from experience, competence and a serious scientific integrity (Beard, 2005). Bellow are presented briefly the recent achievements in the fire simulation community on these topics.

6.3.1 Zone Models

The zone models solve equations governing the fire physics of gas in control volumes which are the enclosures in the ship (Walton, 2002). Some simplifications and assumptions on the gas volume properties must be done (Quintiere, 2002). These models provide good space averages of temperature, gas species and the hot layer height in simple enclosures. For transient application and for larger scales, the field models development have been necessary in order to represent the complex smoke movement, the local flame effects, particularly for the transient and the growing phase of fires.

Zone models have been developed mainly by universities and fire laboratories and are based on simplified set of equation that requires a numerical solver. Field models started to be developed following the development of general Computational Fluid Dynamics codes of the industry. Some of them are well known general CFD codes and other are dedicated to fire and smoke simulations. Zone models and some field models have proven a good accuracy on specific experimental tests.

The limitations of zone models are well known and their accuracy depends on the skill and the knowledge of the user, the complexity of the case to be simulated and the degree of precision of the prediction desired. Although they provide rough estimation, in some cases their use is very profitable because of their calculation speed. They are often used to provide quickly information on the hot layer temperature, concentration of species, layer height and can be combined with detector response tools. They allow sweeping a large amount of scenarios which can combine thousands and thousands of input data which sometime can be defined as statistical distribution of a physical quantity (statistical distribution of fire location, probability of window failure against temperature, etc.), or with probabilistic events (door open/door closed, sprinkler activation success/failure etc) and obtain outputs displayed as statistical quantities. Some developers have interestingly used such a semi-probabilistic approach using Monte Carlo method and zone models. Sometimes, a control of the zone model results with a field model is sufficient to validate a campaign of dozen of zone model simulations. This speed advantage also enables to check some fire scenario during the preliminary analysis of an Alternative Design process (IMO, 2001) and find out the most vulnerable zone or the worst cases.

6.3.2 New Functionalities

Today developments are dedicated mainly to CFD fire models. Almost all the developers are working hard to represent complex safety systems in the simulation. This demand is justified because today, if a free ventilated fire in a brick enclosure is well simulated by most fire models, an under ventilated smouldering fire controlled by a water mist system is a nightmare to predict.

Drenchers, sprinklers and water mist

A suppression system is one of the most critical systems to represent in a fire. The physics and chemistry underneath the fire phenomena are very complex: movement of the droplet, radiation through the fog/spray, vaporisation, wet effect on the solid and liquid combustible etc. This complexity is now resolved in some fire models and it is a one of the most important parts of the current and future development in fire simulation codes. Today, if the physics is better understood and if reliable input data for sprinkler are available, the prediction of their effect on a real fire is still very uncertain (Mawhinney and Back, 2002; Hostikka and McGrattan, 2006).

Pyrolysis models

At the beginning of a fire, flames propagate gradually and locally on materials, and sometimes a flashover occurs, when the thermal atmosphere is sufficient enough to ignite other materials far from the fire seat. These ignition effects and the rate of production of gaseous combustible provided by those materials can be evaluated today by pyrolysis models for solids and evaporation models for liquids. Some developers have recently included routines for these phenomena. They are fascinating since they ought to predict the production of the quantity of gaseous combustible in an enclosure which is the master parameter in a fire. But each material requires its experimental campaign of test to be represented and the fire models requires very thin mesh refinement around these materials when a pyrolysis evaluation is wanted (Hietaniemi *et al*., 2004).

Multilayered boundaries

Ship superstructures are sometimes more complex than the ones of buildings onshore, and they are different in nature. A fire model would need to model the different layers of the separation which are often constituted of several materials, which physically participate to the thermal insulation, and therefore to the temperature and the fire development. Today many models include a multilayer approach to represent the thermal transfer in the boundaries of the enclosures. Still, air gaps and holds are very difficult to model, since the thermal transfer has to be model inside and the convective gas movement must be evaluated.

HVAC systems and leaks

At the early stage of a fire, HVAC systems are the first oxygen provider in an enclosure of a ship and their role is very important to simulate the fire escalation. But climatic atmosphere balance in the ship is a discipline by itself and many codes did not account of that. Recently some codes have made efforts to correctly represent fan curves, air conditioning vents etc. But still, the whole climatic system and a clear modelling of the cut of the system, when the fire is detected, have still a margin of progress particularly for ship design.

On another hand, leakage and porosity in separation always exist and some models have made interesting progress to represent them. Nevertheless, again the input values to provide are almost inaccessible since there is no standard to evaluate a leakage rate in a ship separation.

Interaction with the occupant
In fire simulation, the amount of modelling effort to represent physics and automated activation etc is huge. Interaction with the occupant is one step more to foresee. It is probable that some action from human may disturb, if not change, the fire development and therefore radically change the fire behaviour. The main example is that a fire door is probably closed after the fire alarm, except if a hundred of people need to evacuate through, possibly letting smoke evacuate and fresh air coming in the compartment in fire. Developers today are close to this step since evacuation software, which take crew action into consideration and fire models can be coupled (see bellow).

6.3.3 Simulation Speed and User Needs

Because of the huge progress of computers, calculation times have decreased. But from the user side the effect is that the user simulates scenarios he wouldn't have had time to simulate some years before, or the user uses more complex models applied on larger geometry, because he/she was previously restrained by the limitation of computers. In fact, he/she would have need to simulate those scenarios or to simulate fire in greater details in order to tackle uncertainties of input scenarios or too conservative assumptions one was obliged to take because of uncertainty of the model.

Many codes have been an agglomeration of routines and have added continuously other routines. This lead to non-optimised programs. A huge work of assembly of these routines had to be undertaken. Moreover, some selection and program optimisation had to be performed to spend effort and distribute the calculation time on physical phenomena that really impact the results (McGrattan, 2007).

Generalist codes had an advantage on purpose developed fire codes: they where integrated in a user-friendly interface. Early fire codes where laboratory codes that required specialised post-process and where inapt for a large distribution. Now most of the codes have their input and output engine which are specially fitted to the definition of a fire design scenario and to a reliable and quick interpretation of the outputs. Designers' CAD files are read into the software and the preparation to run a fire simulation demand less and less uninteresting work of 3D geometrical representation in the fire model, to save engineering time and to concentrate on the fire design scenario parameters.

Depending on the software a database for simple materials is provided inside the software. These databases include thermal properties (Ewer *et al.* , 2008) as well as combustion and pyrolysis properties. One should pay attention to the impact of the default values on his/her simulation and take care that his/her material to be represented corresponds well to the one defined in the software. Attention should be paid that materials defined by default in fire models are material for onshore building, which are different and for which norms (even norms for fire protection) are different.

Another gap that is beginning to be seen is the difference of the inputs required by the ever and ever complex fire models and the real availability of these data during the construction of a ship or worse during the pre-project when materials and layout can change. At a research scale, it is possible to examine the details of the numerical inputs, and to valid their value within a campaign of fire test. Some developer had stopped providing input default values after reporting bad use from the public (McGrattan *et al*., 2007).

For a global fire safety analysis, fire models are to be coupled, ie to communicate, with other engineering software as CAD software, risk models, structural models and evacuation models. Ship superstructure inputs come from general arrangement and fire safety plan in a CAD format (Haupt, *et al.* , 2005; Frost *et al.* , 2001). Each designer has his own standards for those files. The ability of interpretation by the pre-processor of these CAD files is different from one fire model to another. Development of a normalised standard to select fire design scenario information into a CAD file might be very optimistic but could really help to concentrate on fire safety problems rather than communication problems.

When fire model outputs are used to feed a risk model usually it is done manually. Nevertheless, it is possible to couple simple and quick fire models, with the restriction mentioned above, to risk based model and for decision support. Nowadays, it has been realised easily with zone models. It has not been attempted with CFD model for obvious calculation time reasons.

Fire model outputs are also used to feed a structural analysis model, automatic procedures are under development and the ability to simulate local thermal radiation and shadow effect on steel structures (Kumer *et al.* , 2006) has been demonstrated. Today the data transfer is one way (a CFD simulation is run independently of the structural calculation and results), and two way coupling (changing in the structure or geometry does not feed back to the CFD calculation) has not yet been. Some developers now propose a minimal set of outputs directly reusable in thermo-structural software via comma separated files (Duthinh, *et al.* , 2008). Finally, fire models outputs can be used to feed a smoke model in an evacuation model which are used by a toxicity and heat effect sub-model. Today some fire models are developed to have an automatic data transfer between them (Galea *et al.* , 2003; Hostikka *et al.* , 2006).

6.3.4 Summary

Because fire hazards are highly complex phenomena, the general aim to predict the development of a real fire, or to simulate accurately very specific phenomena, fire models still have milestones to attain. There will always be a difficulty to combine the need to run several scenarios cases and to model thinner and thinner phenomena. Couplings with design software, with evacuation software and with structural software are a good axis of research for the next decade.

But the aim of fire safety engineer in the maritime world can be, at a first level, to tell if a design is acceptable or not, given an accepted design reference, as the Alternative Design and Arrangements for Fire Safety Guidelines recommend. Some of these fire simulation tools are yet sufficiently powerful and accurate to compare, when possible, to the fire safety performance of an alternative design with a prescriptive design on given relatively risky scenarios. When comparison is not possible, an absolute analysis may be possible; yet, it has to be comforted by a difficult validation procedure, or by otherwise well defined safety assessment. Bureau Veritas is working on this topic to include global risk assessment models in the Fireproof project.

7. CONCLUSIONS

In recent years, multi-agent based ship design decision systems have received a great deal of attention and distributed synchronous cooperative ship design via the internet is becoming more than a new research field. For this development, the multi criteria design making environment requires a new optimisation approach which is suitable for multi-agent system whilst still being simple and efficient.

Ship design companies handle a large number of requests for tender annually. These tendering projects are typically resource-intensive, time critical, with a high risk. Though some of these projects will be novel designs, the bulk will be customizations and modifications of an existing design platform. The traditional approach to handle this process has been to copy an existing project, and incorporate the necessary changes. However, this process is both inefficient and error-prone, and recent developments in platform-based design and mass customization offer opportunities for improvements.

In the framework of recent progress in the field of ship design and ship structure optimisation, we must highlight tool developments for the purposes of enhanced “Design for Production”. All these subjects are discussed by Committee V.3 “Materials and Fabrication Technology” and materials will not be repeated here. Let us nevertheless mention that the main trends are:

- Make simulation more accessible
- Standardisation of databases systems to avoid interfaces
- Integrate optimisation inside production simulation loop
- Include outfitting in the simulation loop

Indeed, in some shipyards, simulation is already well established for supporting decisions in production and planning. Simulation of production process enables pre-estimation and virtual testing of different production planning scenarios, leading to the best solution. Trying to define what "Design" means in shipbuilding, one could identify some basic activities related to naval architecture: body plan, general arrangement, hull classification drawings, etc., which represent the design core. Mentioned documents are usually developed either by the yard itself (provided it is big enough to host a dedicated design department) or supplied by the Owner or one of his consultants (generally in case of smaller shipbuilding companies and low/medium size constructions).

With the aim of concurrent engineering, the output from different design tools should be merged into a common field (usually merely graphical as a CAD environment): in such a way everything is fully integrated, which means, for example, that 3D machinery/outfitting arrangement takes account of hull structure and vice-versa (engine layout, casings, escapes, ducts, piping, etc.). The graphic common environment also allows the designers to exploit hybrid views of the ship on general arrangements, sometimes hardly possible as "saved views" from a real 3D model. The design tools should also support the production engineering of the ship, giving the designer the opportunity to check the feasibility of his choices in real time (maximum blocks weight, maximum dimensions of developed plates, etc.). In general, as the work is often developed by subcontractors (much more than in the past), commercial software codes are preferred to in-house developed ones, for both pure graphics and more complicated documents. However, in the spite of this general trend, there are some design companies interested in developing of their own software. For example, CARENA, the software code developed in Ship Design Group Galati, Romania. This software contains graphics and documents ready to be delivered to the customers. To satisfy their own design necessities they developed integrated software codes for inclusion of applications such as SURF – AUTOCAD – NUPAS – NESTIX (Chirica, *et al.* , 2008).

Still concurrent engineering is perhaps an uncommon procedure for many yards. The big lack in structural design, as underlined by most of the designers all over the world, is the absence of a unique tool that could be efficiently used from basic to detail design: product oriented software can hardly be used in early design stages, because it is not flexible enough to ensure that complex geometries and associated objects can be quickly generated and modified (even several times during the same project development). It is also actually difficult to customize by ordinary users.

On the contrary, parametric and topological systems may properly cover the design until a certain level of detail providing the required level of information for a certain phase (classification drawings or little more) but are limited when the need is to automatically send information for production purposes.

In both cases, a duplicate model must be carried out, which means that the structural definition has to be partially transferred or reconstructed by copying previous ones into another system, with a consequent loss of time and a possible loss of accuracy.

Today's challenge for design methods should perhaps not be to create the "magic button", capable of generating the ship and any kind of simulation with the same tool, but possibly to try to set a common philosophy between the two creative/productive design phases, individuating the connection points between them and finding a rational and more efficient way to transfer the information from basic design systems to product oriented ones. Fortunately the many needs for today's designers are becoming more commonly addressed world-wide, with substantial progress being developed on many fronts.

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