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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

Ship design methods, computer tools, computer aided design, computer aided engineering, lifecycle management, databases, PLM, integrated tools, multi-level optimization, surrogate modeling.

CONTENTS

1 INTRODUCTION

The Committee was very enthusiastic to address the mandate we received. For years, and may be centuries, ship design has been an independent activity taking place at the beginning of the ship's life. More recently, the data associated with the design and production steps carried out in the shipyard have been transferred to external bodies such as class societies or ship owners to allow a more efficient maintenance, repair and disposal of the vessel. Unfortunately today such data transfers are still done on a case by case basis and not globally standardized. The Committee is convinced that in the near future data integration will become a reality for the lifecycle of a ship, connecting shipbuilding and shipping companies. We do not envision this integration coming from the unreachable Nirvana of a single central database that is shared throughout the design phase and then exported outside the shipyard. We instead see this arising from a usable set of data, which will be soon made mandatory by the regulation, linked to one ship and that can be consulted and edited for the whole lifecycle of the ship by all the stakeholders (ship owner, repair yards, class society ...). This upcoming transition is the reason why we decided to make Life Cycle Management (LCM) the central focus of this report.

From our point of view, any kind of industrial activity is strongly influenced by the cost. For LCM, a key principle is the overall product life cycle cost (LCC). This cost is divided into various components:

- its purchasing costs (often called capital expenditures or CAPEX);
- its exploitation costs (often called operational expenditures or OPEX);
- its disposal costs (included or not in the OPEX or CAPEX depending of the product).

Sometimes more detailed formulae may be used to identify various components. An example formula may be described as follows:

$$LCC = C_{ic} + C_{co} + C_e + C_p + C_m + C_s + C_{env} + C_d$$

with:

- C_{ic} = Initial cost (initial investment or CAPEX)
- C_{co} = Commissioning costs (often included in the CAPEX)
- C_e = Energy costs (included in the OPEX)
- C_p = Exploitation costs (personnel included in the OPEX)
- C_m = Maintenance and repair costs (included in the OPEX)
- C_s = Loss of income costs linked to a production stop (included in the OPEX)
- C_{env} = Environment related costs (included in the OPEX)
- C_d = Disposal costs

A ship owner is obviously facing a very competitive marketplace and must seek to minimize vessel LCC as much as possible. The onus to do so is in turn transferred not only to shipyards but also to all activities involved during the ship operation and disposal. So, what we term LCM in this report includes all the methods, tools and, procedures the shipping community (including all actors from the shipyard to the disposal yard, including ship owner and classification society) must employee in order to keep the overall LCC of a ship as low as possible. The cheapest ship is not obviously the one with the lowest initial sale price. It is the one that costs its owners the least amount of money from conceptual design to disposal.

As defined by the mandate we gathered data from both commercial shipping and navies. The drivers for LCM regarding state owned ships differ from those applied in private companies. Nevertheless, all ship owners apply a LCM framework to a certain extent and we hope that the mutual comparison will be useful to every reader.

We will introduce the needs and requirements together with the drivers for a life cycle oriented design which we called design for lifecycle. To achieve design for lifecycle, existing tools and methods must be employed along with some newly developed approaches. In this report, we present both the existing tools and methods as well as highlight remaining areas of conflict or future development. We demonstrate how these methods and tools can be integrated into practical and convenient solutions for the stakeholders. Finally we present some existing and, more or less integrated solutions together with the obstacles which currently prevent software vendors from offering more integrated solutions and suppressing the demand for lifecycle solutions from the end users of the tool.

The main problem we faced in developing this report was the lack of reliable and consistent information. The cost aspects are always touchy and it is very difficult to get realistic and useful data. Nevertheless, we decided to try our best to get enough data to display a realistic picture of what we are aiming to demonstrate in this report. To do so we used two common methods of obtaining data.

Our first source of data is a literature survey based on public data. This includes books and PhD theses, journals, congresses and conferences proceedings and web sites. It also comes from public data issued by public funded projects such as European Union projects. Recently, an extensive analysis of the outcomes of European maritime research projects in FP5 to FP7 has been carried out in the European project MARPOS (2011). This analysis includes Chapters on Competitive Ship Design Methods, Integrated Life Cycle Services and on Improving Safety by Design, which provide further information in relation to the scope of work of this Committee.

Our second source of information came from a new survey commissioned by the committee. We built a survey based on our experience and topics we were looking for more information from. Each member has been in charge of contacts located in his or her geographical region. We received 23 answers to the survey. Unfortunately, most answers came from Europe and the limited amount of data not enough to draw real "statistical" worldwide conclusions. In the framework of an ISSC Committee where we had to find volunteers to fill in the survey, the responses received were viewed as significant enough in number, and we decided to use the data coming from the survey. A comprehensive summary of the survey results is presented in section 9.

Finally, the Committee would like to express special thanks to two major contributors who helped a lot in this report edition by their contribution to chapters and management of the survey: Jean-David Caprace from University of Liège in Belgium and Martin Bergstroem from CMT in Germany.

2 DESIGN FOR LIFE CYCLE

2.1 Integrated Life Cycle Management

According to Fiksel (1996), Integrated Life Cycle Management (ILCM) can be defined as a comprehensive and flexible life cycle framework for making planning, design, and operating decisions, explicitly considering costs and other fundamental business metrics together with environmental, health, and safety factors. ILCM is thereby an overarching system of concepts, methods, and practices that can be used to effectively manage a ship from cradle to grave. The framework includes all actors at all stages of the production and operation of a ship. According to the Quality Associates (2011) the fundamental components of the system include the organization, resources and processes. Consequently, people, equipment and business culture are part of the system as well as the documented policies and practices.

The general objective of ILCM is to reach long term sustainability by combining human requirements (such as safety, usability, and comfort), environmental friendliness, and profitability. In other words, the specific goal is to minimize the environmental impact while at the same time maximizing the long term profitability. Sharma and Kim (2010) state that the key to retain efficiency and economy is to manage resources in a collaborative and integrated environment that synchronizes with various requirements of customers, design firm/unit, production (shipyard), rules and regulation (classification society), outsourced collaborators etc. By integrating all systems and processes into one framework, it becomes possible to find out how various factors affect each other etc., which enables optimization of the overall life cycle performance of the ship. Obviously, this provides significant benefits in comparison with an un-integrated management system that only would enable optimization on sub-system level.

It has already been mentioned that an ILCM system should involve all actors at all stages in the production and operation of a ship. Thus, and ILCM system should involve the following types of management systems (here the term management means the process involving performance monitoring, decisions making, implementation of adjustments if necessary, etc.);

- Environmental management
- Quality management
- Logistics management
- Maintenance management
- Health and safety management
- Social responsibility management
- Etc.

Obviously, to make the different systems properly integrated, effective linkages between various management systems are needed. In addition, to successfully adopt and implement a life cycle management approach, it is necessary to maintain a consistent life-cycle perspective. Obviously, this requires an open minded multi-disciplinary approach to all issues.

As mentioned, the ILCM framework should include all significant stages of the production and operation of a ship. Specifically, this means that at least following production stages should be included;

- Raw material acquisition
- Manufacturing of ship building material and components
- Transport of material and components to the shipyard
- Shipyard activities (energy for welding etc, emissions, waste)
- Ship operation (fuel consumption, emissions to air and water, waste, etc.)
- Ship maintenance (materials and energy consumption)
- Final disposal (recycling of materials, hazardous waste, etc.)

The operation phase is generally the most significant in terms of emissions and costs such as carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). In addition, possible discharges into the water (such as oily bilge water, ballast water, untreated grey water, and dangerous substances from antifouling) do also primarily take place during the operation phase. However, to get the whole picture, the production and the end-of-life (recycling or disposal) have to be considered as well. The building phase is especially important in terms of use of material, while the demolition phase is important in terms of environmentally hazardous waste such as non recyclable composites, asbestos, halons etc.

ILCM is on product level executed by applying Product Life Cycle Management (PLM). According to Sharma and Kim (2010), PLM is the process of managing the entire life cycle of a product from its conception, to design and manufacture, to delivery, to maintenance and service, and to finally disposal. PLM integrates human resources, data, design, processes, and business systems. Consequently, PLM is not just about software and data management but is also a business strategy. In addition, Sharma and Kim (2010) point out that PLM describes the engineering aspect of a product and should therefore not be mixed up with for instance product life cycle management (PLCM), which refers to commercial management of a product with respect to sales measures etc.

Sharma and Kim (2010) states that to make a PLM system work, it has to be built on top of CAD/CAM/CAE, PDM, and enterprise resource planning depending on the type of the primary user. The conceptual development and the basic building concepts for a logic based PLM system for the shipbuilding industry were presented by Sharma and Kim (2010). The logic bases of the presented system consist of modularization, standardization, geographical zoning, and functional zoning. The logic bases of modularization and standardization are used in the ship design and production processes, and the logic bases of geographical zoning and functional zoning are used in “logically grouping” the on-board activities in the ship production process. According to Sharma and Kim (2010) an implementation of the system indicated that the system results in more streamlined and better planned and executed design and production processes.

2.2 Design Loop and Lifecycle Data Management

According to Grogan and Borthen (2010), late changes to a ship’s design are recognized as the primary factor contributing to increasing ship construction costs. Thus, when the US Navy’s Zumwalt class guided missile destroyer was designed, an integrated detailed design was implemented to get the design right before start of production. The integrated design progress was carried out using an Integrated Data Environment (IDE), which makes it possible to freely send and receive information (models, presentations, written documents, charts, and visual issues) in a secure manner while at the same time being able to access the information from any authorized computer at any time. The integrated system was used to maximize the number of stakeholder disciplines that reviewed and critiqued the design. All the reviewers were able to comment on weaknesses in the design. Thanks to the IDE system, production planners participated actively in the detailed design. According to Grogan and Borthen (2010), potential manufacturing difficulties were, thanks to this procedure, found early in the design phase, avoiding them after the construction had started.

Generally the new building process produce a lot of valuable information that later can be used for the optimization of operations, safety, as well as retro fitting and recycling processes etc. By improving the cooperation between all actors in the life cycle chain, this information could be more efficiently used to improve the overall LCP of a ship. In addition, it is well known that the actors in the new building process, i.e., designers, shipyards and equipment suppliers, are often the drivers of innovation and use of technological solutions and skills. Thus, an integrated life cycle data management system could also increase the competitiveness of the repair and retrofitting yards etc. by providing them access to data concerning new technologies. However, Intellectual Property Right (IPR) issues, which of course have to be considered, may pose significant challenges related to this issue. For the balance between IPR and design transparency, a cross industry group included in the GBS Working Group at MSC 82/5/4 (2010) is developing the Ship Construction Files (SCF) Industry Standers supplementing the MSC guidelines. SCF is designed to be mandatory and includes all documents that are sufficient to provide structural and safety information for safe operation and for emergency situation satisfy the GBS functional requirements, and to stay with the ship throughout its lifetime. This concept makes a start of solutions on IPR protection although the GBS will be forced from 2016 only for Bulk Carriers and Double Hull Oil Tankers. More information on IPR in shipbuilding may be found in the European project Guardship web site (2009). Thus, to assure proper work and secure data exchange, the relationship between the shipyard and the maintenance and repair providers has to be confidential. The relationship is especially important when dealing with maintenance of ships featuring unconventional technologies and materials such as composite. Such innovative solutions offer significant operational benefits. However, they can cause problems (including safety problems!) in daily operation if maintenance staff and repair and retrofitting yards are unable to deal with them due to lack of information/knowledge about possible special maintenance/repair procedures etc. Thus, the potential of various innovations cannot be fully used if skills on how to repair and maintain the solutions are not available over the entire life cycle.

2.3 Drivers for an Integrated Life Cycle Management

Shipbuilders and ship operators will in the near future have to adopt more and more life cycle thinking. Sharma and Kim (2010) points out that the modern environment of high efficiency and economy and sustainable environment is demanding ship design that are energy efficient, disposable with minimum damage to the environment, and able to stay in service for longer durations. Obviously, to meet such demands, it is necessary to implement ILCM.

Various LC approaches have already become standard in a number of industries. However, within shipbuilding, life cycle approaches are still not among the established processes. This is likely to change since there are a number of strong drivers for an ILCM. Some of the drivers are purely economical while others are set by various agreements, rules and regulations. The main groups of drivers are listed and discussed below;

- *International agreements, rules and regulations;* The IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational and accidental causes. By taking possible future regulations into account, such as a CO_2 tax, it is possible to design ships with a better long term performance. IHM is another upcoming regulation to be considered, refer to section 4.1.3 for more details.
- *Regional and national agreements;* IMO has set general global limits for air emissions and determined some stricter rules for certain sensitive areas referred to as ECAs (Emission Control Areas) or SECAs (Sulphur Emission Control Areas). EU and HELCOM have regulations and recommendations covering sea areas within the EU and the Baltic Sea. The EU environmental legislation is mainly based on IMO's recommendations. However, EU has developed own legislation concerning ship fuels, antifouling paints, etc. In addition, there are

rules covering special environmental areas such as Galapagos Island. Obviously, a ship designed to meet such regional agreements would be more attractive on the second hand market while it would be suited for a large variety of operations.

- *Initiatives taken by others*; Most of the classification societies offer some kind of Environmental Class Notation. In addition, there are emission based fairway dues to cut the emissions in certain area. For instance, the Swedish fairway system favors environmentally friendly ships by offering them a discounted fairway due. The discount is calculated based on the amount of NO_x and SO_x a ship produce per kWh. HELCOM has given a recommendation and proposed a structure for environment-related fairway dues to its member countries (HELCOM Recommendation 28E/13). Furthermore, some ports give discounts to ships based their environmentally friendliness. Such discounts are given by a number of Swedish and Finnish ports, SPC Finland (2009).
- *Sign of environmental leadership;* increasing public awareness on climate change and environmental protection have made especially passenger ship owners keen to demonstrate environmental awareness to their customers. This has led to ambitious greenhouse gas reduction programs etc.
- *Cost savings;* Better energy efficiency onboard the ship leads of course to fuel savings and furthermore to cost savings. An ILCM can be applied to improve the energy efficiency of a ship resulting in lower fuel costs and emissions. In addition, ILCM can reduce costs by improving maintenance routines. Improved maintenance routines would also result in improved environmental friendliness, and safety. Ships have a long service time and the majority of the total cost of ship ownership accrues during that phase. However, life cycle costs reducing technology is usually "high tech" and demands therefore generally a higher initial investment than standard technology. Thus, shipyards have to be able to demonstrate and convince the ship-owner of the long term advantages of LCC reducing investments.
- *Capitalization of product data*: Briggs *et al.* (2009) stated that the business drivers for IDM are both for the US Navy and for the US shipyards to reduce the costs of ownership and exploit the investment in product data created during acquisition and maintained through the life cycle. Thus, the IDM system must
  - Enable that ships have improved availability, reliability, maintainability, and lower costs if ownership.
  - Reduce IT costs and ensure longevity in use of information
  - Ensure that digital product data are treated as a valuable business asset.
- *Other drivers;* According to Briggs *et al.* (2009) shipyards are increasingly responsible for the life cycle support of ships, including maintenance and logistics data over the life of the ship. The same source points out that life cycle support, repair, maintenance and overhaul, ships operating, testing and training are all information- intensive processes. Hence, it has become important for shipyards to efficiently integrate acquisition product model data with the life cycle support product model data. In addition, the global nature of shipbuilding/shipping and the large number of subcontractors, service providers etc. involved in the building and operation of a ship can of course also be considered as a driver for ILCM. Especially, the building and operation of cruise ships demands integration of a large number of various branches. A typical need for life cycle data is illustrated by an industrial activity just in between shipbuilding and offshore industry. This is when a tanker is converted into an FPSO. The structure remains almost the

same with some additions and subtractions of structural elements, but the main subject to deal with is the fatigue state of the hull to define what the plates to be changed are in order to reach the expected life cycle of the structure taking into account the load history prior purchase.

3 AVAILABLE DESIGN METHODS

3.1 State of the Art in Ship Design Methodology

Design methodology consists of a formal description of the design process, its premises, objectives and procedures. One of its essential foundations is the approach of systems analysis which became known and rapidly spread after the Second World War, Nowacki (2009).

The prevailing design procedure was well captured in the image of the famous design spiral, attributed to Evans (1959) and later also adopted by Hurst (1971) in its early computer systems. This schema correctly depicts the iterative nature of design, but overemphasizes an apparently prescribed sequence of design steps. In practice the procedure varies from case to case and is much more flexible, given that provisional assumptions permit starting subtasks independently. At a later stage when concurrent engineering was pursued, the design team actually endeavored to perform several design subtasks simultaneously. Nevertheless the design spiral served well as guidance in coordinating design activities.

By about 1970 the methods of systems analysis had matured in many other applications and began to make a profound and lasting impact on ship design methodology. Systems analysis serves as a decision-making approach in the analysis, design and operation of large, complex systems. It can equally well be applied to ships, their subsystems and to the fleet or transport system of which the ship may be a part, Andrews (2003).

The approach of systems analysis made a deep impact on ship design methodology, not only because of its greater rigor, but also because it facilitated a coordinated division of labor in the design team. The introduction of computer aids in design enabled each designer to perform a greater share of subtasks in the design process and thus necessitated a reorganization of the division of labor in design. The subtasks of design attained greater scope and granularity, increasing the responsibilities of the individual team member. But systems analysis also provides criteria and methods for harmonizing the results of subsystem design in consonance with overall system performance.

Thus the systems approach has been providing a common platform for many new developments and innovative design techniques for many decades. Many good synoptical papers and textbooks have appeared and have underscored the common denominator in this multitude of new elements in ship design methodology e.g. Rawson (1979), Schneekluth (1980), Erichsen (1982), Andrews (1986), Andreasen (2003), Lamb ed. (2003), Hosoda (2006), Andrews (2009, 2010). The degree of change in ship design methodology during several decades was significant and must be rated by the sum of many individual innovations in this general framework.

3.2 Goals, Achievements and Inefficiencies

3.2.1 Economic Efficiency

Economy remains with safety the most essential goals of commercial ship design. There is no doubt that significant improvements were made in the economic efficiency of ships. The economic assessment of alternatives has become a routine matter in early design stages. A detailed review of different cost assessment methods have been done in ISSC 2006 congress and have been presented by the committees IV.2 and V.3.

The computer made it even more feasible to get an immediate evaluation of economic performance for a proposed design. Design decisions thus have become more transparent and more rational. The sometimes superficially conflicting requirements of economy and safety can usually be reconciled by quantification. Several approaches exist for making these criteria more commensurable.

The future trends are the design for lower lifecycle cost, i.e., shipbuilding and operating cost as well as the design for better product quality, i.e., improved functionality, performance and reliability of the ship. The reduction of the lead time for design and production to achieve shorter time to market is obviously also an important issue.

3.2.2 Ship Safety and Risk Assessment

Ship safety requirements are as essential to shipping ventures as economic objectives. This concerns the safety of human lives, the risks of damage to or loss of ship and cargo, and the hazards to the environment. In fact it is the art of ship design to find solutions meeting both economic and safety requirements without compromising any safety principles.

For many decades the management of safety in design has been a matter of improving regulatory requirements in response to experience with fatalities, damage or loss, by conventions issued by international agencies and institutions such as SOLAS and IMO. This is still necessary to set standards and reach international agreement.

Probabilistic methods for risk assessment have now gained full acceptance and are in practice replacing older deterministic, safety factor based regulations. Calculation methods for predicting ship performance in critical situations, in a seaway or in collisions and groundings, have been further developed. Extreme catastrophes, say, by monster waves or tsunamis, are investigated and taken into consideration. Quantification of risks in early design stages is becoming more and more feasible, Papanikolaou (2009). Pursuing risk based design approach quantifying all hazards is the future trend.

From a regulatory point of view, Formal Safety Assessment (FSA) has been the primary approach to analyze the cost benefit of new or changed regulations. FSA comprise a systematic methodology to identify hazards, assessing the risks related to these hazards, and determining the cost/benefit of alternative risk control options. The result can thus be used to make better informed decisions on regulatory changes, balancing the benefits in terms of expected reduction in lives lost or reduced pollution, against the cost both for individual parties as well as the industry as a whole. Several FSA studies have been developed as input to the work in IMO MSC, Papanikolaou (2009), as well as in the EU funded SAFEDOR project.

From a design perspective, FSA is important for promoting goal based standards to support the design of new and innovative designs, as an alternative to prescriptive rules presupposing a specific technical solution. By explicitly defining the safety objective to be met, alternative design solutions meeting the same standard may be approved. This also opens up for risk based acceptance criteria, with classification societies using the FSA guidelines as basis for own rule development, Skjong (2009).

3.2.3 Rationality and Probabilistic Modeling

Many influences on ship performance are uncertain at the design stage, in particular the hazards of loads and safety. The environment of the ship in an irregular seaway and the events involved in ship collisions and groundings are examples of random processes that need to be described in terms of probabilities. Fortunately some pioneering work has made these processes amenable to probabilistic modeling. Recent applications, e.g. in the compartmentation of double hull tankers, Papanikolaou (2009), in design optimization, Diez *et al.* (2010), Hamada (2010), Okasha (2010), are giving new significance to such models. Design for structural reliability belongs to the same category. Therefore in recent decades several computational methods have been introduced and have become routinely applied in ship design, where appropriate, to evaluate risks and contend with uncertainties.

3.2.4 Optimization

In the framework of the systems approach optimization methods have become the favorite design solution tool. Many of the principal stages of the design process have been approached by optimization, Nowacki (2003), Bertram (2003), and Vasudevan (2008). The approach is invaluable for innovative design tasks and may confirm and thus reassure the solutions to more conventional design applications.

The advantage of using optimization in design is not only the ease of finding the best possible solution(s) more or less automatically, but also having the assurance that improvements are no longer feasible by small changes in the design variables. It is an important result also to learn which constraints are governing the solution, sometimes in order to soften certain constraints.

The nonlinear optimization problem does not necessarily yield a unique solution, in multimodal cases several local optima exist. It is of value to know multiple optima if they exist. To enumerate several or all local optima necessitates a conscientious inspection of the whole feasible design space.

Problem formulations with multiple goal criteria have become popular in ship design. This tends to occur when economic and safety indicators are both taken into account as equivalent goals. One possible approach to this dilemma consists of Multiple Criteria Optimization (MCO). MCO methods, e.g. Pareto optimization, help to define the most suitable compromises. See more methods and examples in chapter 5.

3.2.5 Integration

It was one of the earliest dreams in CAD/CAM to have available an integrated, coherent software system that would support the entire design process, Roos (1967). This meant that a set of design methods would share a certain database and build up the product model in successive design steps, not necessarily in any prescribed sequence. Thus the methods would be interfaced by sharing data sets in the database. The designer would be able to perform design steps in any desired and meaningful order without unnecessary responsibility for input and output.

The demand for fully integrated systems is undiminished. In practice some external and even in-house interfaces remain heterogeneous. Chances for integration have improved by standardization (STEP) and by building neutral connectors. The idea of standardizing product model representations is helpful, too. Yet on a larger scale integration is not yet fully realized, Boesche (2010).

3.2.6 Open Communication

The communication between heterogeneous CAD/CAM systems and subsystems is now recognized as a key prerequisite for digital collaboration between suppliers and customers. The standardization in STEP and similar standards shows an approach for neutralizing the interfaces. However open product model communication between distributed partners has not yet been fully achieved, especially if the systems differ in functionality, Bronsart *et al.* (2005), Guyt *et al.* (2005), Thomson (2010), Briggs (2009).

3.2.7 Versatility

In ship design the lot size is usually one. Changes will always occur before and during production. Thus CAD/CAM systems must be extremely versatile to contend with ever changing design requirements. CAD systems during several decades have certainly become more comprehensive in scope and hence more versatile. Some system vendors claim to cover the complete CAD-CAM-CIM cycle. Exceptions from this trend still occur with new floating structures such as offshore wind mills and features as well as unconventional design objectives. Simulation and visualization have added to system versatility. The trend is in the right direction.

3.2.8 Simulation and Visualization

Simulation and visualization together ("the virtual ship") are also increasingly used in early stage design to display the product model of the ship in three-dimensional views together with its operating systems in order to review the geometry, subdivision and structure, for investigating issues of production and operation or safety hazards and emergencies, the performance of lifesaving systems and many other operational scenarios, Kanerva (2002), Lödding (2011). More considerations on production simulation and virtual reality are presented in the committee ISSC 2012 V.3.

3.3 Design for X = Current Practice

Today ship design can be viewed as an *ad hoc* process. It must be considered in the context of integration with other design development activities, such as production, costing, quality control, etc. In that context, it is possible for the designer to work on a difficult product, requiring high material or labor cost, and containing some design flaws that the production engineers have to correct or send back a new design before production. Any adjustment required after the design stage will result in a high penalty of extra time and cost, Olcer (2004). Deficiencies in the design of a ship will influence the succeeding stages of production. In addition to designing a ship that fulfils producibility requirements, it is also desirable to design a ship that satisfies risk, performance, cost, and customer requirements criteria. More recently, environmental concerns, safety, passenger comfort, and life-cycle issues are becoming essential parts of the current shipbuilding industry.

With this paradigm, the selected design will be a producible, cost-effective, safe, clean, and functionally efficient design. This will enable shipyards to obtain great rewards, such as the reduction of construction time and costs, reduction of lead time, improving product quality, simplification of products, and gaining sustainable competitive advantages in the shipbuilding market.

Throughout the engineering disciplines, many "Design for X" (DFX) processes have been developed in order to correct the inadequacies of the designs during the ship design stages. DFX is the process of pro-actively designing products to optimize all the functions throughout the life of the product. This has been called "Design for X" where X is whatever the specific focus happens to be. So "Design for X paradigm" covers many areas such as Design for Production, Design for Manufacturing, Design for Assembly, Design to Cost, Design for Simplicity, Design for Maintenance, Design for environment, Design for Safety, Design for Life Cycle Cost, Design for Robustness, Design for Six Sigma, etc.

3.3.1 Design for Cost

Design to cost (DTC) is a management strategy and supporting methodologies to achieve an affordable product by treating target cost as an independent design parameter that needs to be achieved during the development of a product. DTC is an area which has attracted much attention recently. The objective with DTC is to make the design converge to an acceptable cost, rather than to let the cost converge to design, Rush (2000), Ou-Yang (1997). DTC can produce massive savings on product cost before production begins. The basic concept of DTC is to estimate the manufacturing cost during the conceptual and early design stages in order to achieve the following objectives:

- To identify the model parts that might cause high manufacturing costs.
- To provide an environment to estimate alternative cost for comparative design models.

The general approach is to set a cost goal, then allocate the cost goal to all the elements of the product. Designers must then confine their approaches to set alternatives that satisfy the cost constraint, Michaels (1989). The control of costs to meet these objectives is achieved by practical trade-off involving mission capability, performance and other schedule objectives.

However, this is only possible once cost engineers have developed a tool set that designers can use to determine the impact of their decisions as they make them. Caprace (2010) presented different developments to help the designer analyze the impact of their decisions on the ship cycle.

A detailed analysis of the concept of design for production, design for manufacturing and design for assembly is available in ISSC 2012 V.3.

3.3.2 Design for Maintenance

Consideration of product maintainability and reliability tends to be an afterthought in the design of ships. The design of the support processes needs to be developed in parallel with the design of the ship and not after. Parallel design can lead to lower overall life cycle costs and a product design that is optimized to its maintenance processes. Maintenance characteristics of the design and particularly unplanned maintenance are very important mainly because they lead to a reduction in operability, and hence profit in the case of commercial vessels or the ability to complete the desire mission in the case of naval vessels.

Engineering techniques can be applied to systems design to minimize the time and effort required to perform periodic preventive maintenance as well as unscheduled maintenance. Some recommendations can be given to achieve higher quality, better reliability, lower operating cost, and better maintainability. For instance, Kenneth (2007):

- Reduce the number of parts to minimize the possibility of a defective part or an assembly error

- Reduce the complexity and time of the assembly/disassembly process
- Improve the accessibility for testing or inspections of the components of the product
- Apply DFA to minimize non-value-added manual effort during the assembly of the product
- Use modular design for components with greater probability of replacement to facilitate assembly/disassembly
- Utilize standard parts to minimize the amount of spare parts
- Provide self test and self-diagnosis as more as possible
- Ease piping connections (i.e. flange connection)

3.3.3 Design for Environment

Design for environment (DFE) is a relatively new field, developed in parallel to pollution prevention. The aims of DFE are to minimize raw material consumption, energy and natural resource consumption, waste/pollution generation, health and safety risks, and ecological degradation over the entire life of the ship, Barentine (1996).

DFE integrates environmental considerations into the design of ships with a better environmental performance over the ship's entire life cycle. Decisions made about the types of materials and other resources, as well as manufacturing processes to be used during production, affect the environmental performance of the ship. Following the finished design, the ship's environmental attributes are generally fixed and cannot be changed (Olcer, 2004). Therefore, a systematic integration of environmental considerations into the earlier stages of design is essential to achieve increased environmental performance. Incorporating DFE attributes into ship design has some benefits, such as reduced energy and material use, reduction of emissions and waste, focus on material selection issues: design for recycling, design for disassembly, management of toxic materials, and evaluation of environmental attributes.

The reader may find more details regarding the design for environment approach by referring the section 4.1.3.

3.3.4 Design for Safety

Rather than waiting for an accident to happen and then act in haste to set up new rules, all pertinent knowledge deriving from such accidents could be analyzed and stored to improve the safety as early as possible in the design process. Today, it is widely accepted that rules provide minimum standards on average and in some areas there are not even rules to provide minimum standards of safety. Consequently, Design for safety (DFS) should systematically integrate risk analysis in the ship design process with prevention/reduction of risk (to life, property, and the environment) embedded as a design evaluation attribute.

DFS is a real opportunity for ship owners to have ships customized to their needs while maintaining the same safety levels. However, DFS is a very expensive and time consuming approach, Birmingham (2000). Indeed, the resources required for additional safety during the design stage will inevitably have a cost. It is from this background that the marine DFS emerged. The key drivers of the philosophy are to keep safety as an important functional characteristic of the design and to speed up the process of risk and cost analysis, so that the process itself becomes more usable. IMO, MSC, SOLAS, ISO, IACS, and MARPOL are continuously improving and implementing the safety requirements in the shipbuilding industry. In particular, the IMO Maritime Safety Committee MSC recently adopted a new philosophy and a working approach for developing safety standards for passenger ships, Papanikolaou (2009). In this approach, modern safety expectations are expressed as a set of specific safety goals and objectives, addressing design, operation and decision making in emergency situations with special attention paid to flooding survival analysis and fire safety analysis.

3.3.5 Design for Retrofitting and Refurbishment

Retrofitting and refurbishment are significant cost factors in the life cycle of a ship. Retrofitting and refurbishment is being carried out mainly for the following reasons:

- To adopt ships to meet upcoming safety and environmental regulations, e.g. related to double hull structures for inland waterway ships or to meet new regulations in regard to gas emissions;
- To adopt the interior of passenger ships to varying passenger needs and comfort requirements and
- To adopt ships to new operational tasks, e.g. the conversion of tankers into FPSO etc.

For complex ships, the cost related to refurbishment can reach the order of magnitude of the original investment, i.e. of the production cost. Even if retrofitting is in many cases not driven by structural aspects, the structure of a ship is often affected by changes in the outfitting part. Methods for an efficient "Design for Retrofitting" are therefore important to consider in this report.

The European Integrated Project BESST (2011) includes, among other aspects of life cycle performance improvements for passenger ships a specific work package on Design for Easy Refurbishment. Two European projects started in 2011 are looking into refurbishment and related design methods for improving the hydrodynamic performance of ships GRIP (2011) and the overall energy efficiency RETROFIT (2011). The project MOVE-IT is looking into refurbishment of existing inland waterway ships both to comply with new structural regulations and to improve energy efficiency MOVE-IT (2011). Another European project is looking to establish current practice in particular on smaller European shipyards ECO-REFITEC (2010).

Basing on the projects mentioned above, the following challenges are being addressed with regard to Design for Retrofitting:

- Availability of Data for Retrofitting: a focus of research is to ensure consistency of data from the new building phase, which can form the basis of retrofitting. As its must be assumed for different reasons, that in many cases geometrical and other data needed to design and plan retrofitting will not be available, projects are focusing on measurement systems and the integration of measured information into CAD models for retrofitting.
- Decision Making Tools for Retrofitting: focus of research is put to develop tools helping ship owners and other stake holders to assess the benefits and feasibility of retrofitting. Those tools aim to balance the cost of retrofitting (components and production) versus the life cycle benefits (fuel cost etc.).
- Modularization appears to be the way to promote Design for Retrofitting. It will provide standard interfaces in structures as well as in outfitting (supply of energy and media) and provide the necessary balance between economy of scale (standard components) and flexibility to cope with customer needs by combining those standard components.
- Planning of Retrofitting Processes: Time is a critical factor for retrofitting. It not only influences the direct cost of retrofitting, but mainly reduces the earnings

of the owners. Research is therefore focusing to develop tools which will improve the planning of retrofitting processes, based on the limited amount of information and considering the variety of processes and work operations.

3.3.6 Design for Robustness

Robustness is defined as insensitivity (or stability) with respect to uncontrollable parameters and is becoming a standard concept, particularly for innovative designs. Many input parameters (e.g. loads, material data, thickness, etc.) held constant during the optimization process, are subject to uncertainties causing variations of the values in the criteria set and/or violation of constraints (infeasible design). They can also be costly to control. One way is to introduce safety margins on the constraints, but this leads to a reduction of the design space. Robust design has been developed with the expectation that an insensitive design can be obtained (robust means that the product or process performs consistently on target and is relatively insensitive to factors that are difficult to control).

The robustness measure η, developed by G. Taguchi, Ross (1988), Montgomery (1991), Cho (2006), is the ratio of the mean of the attribute value μ to the standard deviation σ resulting from uncertain parameter values. In fact it is the ratio of predictability versus unpredictability.

The robust design method greatly improves engineering productivity, Isixsigma (2009). Variation reduction is universally recognized as a key to reliability and productivity improvement. There are many approaches to reducing the variability, each one having its place in the product development cycle. The robustness strategy provides the crucial methodology for systematically arriving at solutions that make designs less sensitive to various causes of variation. It can be used for optimizing product design as well as for the manufacturing process design.

4 AVAILABLE MODELLING AND ANALYSIS TOOLS

4.1 State of the Art

The current state in the development of tools for the design of marine structures is characterized by increased scope, integration and the transfer of advanced analysis tools into the early stages of design. Design tools tend to continuously add functionality, covering additional aspects of technical, economic, environmental, risk and safety related performance of the vessel to be designed. Advanced types of analyses, using finite element analysis and computational fluid mechanics, are slowly moving from being used from the detail design stages into early design. This additional functionality is more seamlessly integrated into a common design package, either by relying on a common design representation, or by the efficient translation and exchange between multiple file formats.

4.1.1 Naval Architecture Packages

Naval architecture software tools are ranging in functionality from relatively simple calculations of hydrostatics, to advanced packages with integrated support for the analysis of multiple ship performance aspects.

Traditionally, a preliminary naval architecture design package will comprise the following functionality

- Hull definition, with various levels of lines manipulation and parametric hull form definition

- Internal geometry and compartments
- Basic hydrostatic and stability calculations
- Hull resistance estimation based on empirical methods, speed and power prediction
- Simple methods for sea keeping and maneuvering

In addition, such a package may contain simple weight and cost estimation functions, sometimes combined with required freight rate (RFR) calculations.

In recent years, additional aspects of overall ship performance have been integrated into these tools. This includes computational fluid dynamics (CFD), probabilistic stability calculation, risk based design methods, and environmental analysis.

CFD analysis has so far mainly been used in the detail design of the hull, both for optimizing a given hull form for resistance, hull-propeller interaction and sea keeping, and for verifying the final design towards contractual speed and powering requirements. In the early design stages, characterized by a wider search through the design space for preferable design solutions, CFD applications have been less used. The primary reason for this has been the high cost, in terms of time and computational effort, for the evaluation of each design alternative. Contrary to what should be expected, computational times of CFD analysis have increased over the years due to the demand for meshing detail and flow complexity increasing at a faster pace than the growth in computational power, Peric and Bertram (2011).

However, even if computational time *per* se in many cases has increased, the total effort involved in CFD projects has decreased, mainly as a result of more efficient pre-processing stages. Recent developments with respect to modeling effectiveness through seamless integration with shipbuilding CAD have paved the way for CFD based analysis also in the early stages. This has been supported by many of the commonly used naval architectural design packages either by offering CFD calculations internally, for instance for wave resistance calculations, or by providing an integration mechanism for exporting the hull description with an external CFD tool, Lee *et al.* (2010), Korbetis and Georgoulas (2011), and for the import of the resulting performance data to be stored as part of the CAD model. Examples are NAPA and Friendship Systems.

We have also seen a continuous development of the scope and functionality of CFD tools. Examples of this is the handling of very complex geometry, including moving parts, modeling turbulence, free surface effects and cavitation, motion of floating bodies and fluid structure interaction. This development can be expected to continue, as well as integrating these types of analysis into the overall ship design process.

The integration of environmental analysis into existing ship design tools has mainly centered around the Energy Efficiency Design Index (EEDI), integrating the automatic calculation of this index to be used as a criteria for identifying energy efficient design solutions, Hagen and Grimstad (2010), Harris *et al.* (2011). Alternative approaches has been the use of life cycle analysis (LCA) as a means to capture the total environmental impact of a given vessel design, Ellingsen Fet (2002), or by explicitly considering both present and future emission regulations as part of an optimization model, Balland *et al.* (2010), Balland *et al.* (2011).

We have also seen examples of economic measures of merit integrated into the early stages of the ship design process. Typically this will focus on minimizing the RFR for transport vessels, Harris *et al.* (2011). For non-transport ships, such as offshore support vessels, the RFR is less relevant. Here, the income earning potential of a particular design should rather focus on its appropriateness towards future contract scenarios, Erikstad *et al.* (2011).

Another important development trend is risk-based design, Papanikolaou (2009), which is moving from the realm of research into naval architecture design packages. The concept of risk-based design covers all aspects of the ship design process where probabilistic risk and safety criteria are key drivers in the process, where quantifiable risk levels are used to meet given safety performance requirements. The primary focus so far has been on probabilistic damage stability calculations. This has contributed to a higher degree of design freedom, by allowing alternative vessel arrangements given that the overall safety level can be proved to be equal or above the level corresponding to what is required from deterministic stability regulations. At the same time the application of a risk-based approach has increased the total workload in the design process. Thus the need for efficient tool support has been imminent, and the major providers of ship design applications has responded by integrating support for probabilistic stability calculations in their naval architecture design packages.

An area that has received considerable attention in recent years is the design of ship arrangements. This can be seen as part of a wider process of configuration-based design, placing emphasis on the early design conceptual layout of the design solution. The building-block approach developed by UCL, Andrews and Pawling (2007) has been central to this development, allowing for a more creative, flexible development of multiple conceptual solutions based on alternative configuration of a set of modules derived from the ship's functional specification. The motivation has not only been to improve the result of the ship design process as such, but also to provide insight into the main design tradeoffs that has to be made between multiple conflicting objectives. This supports what is termed a "requirements elucidation" process, addressing the question about what the design specification should be in the first place. The building-block approach has been implemented as part of the GRC Paramarine CAD system. Practical applications have been mainly naval vessel, but the method as such has also been applied to commercial vessels.

Another approach towards ICT support for ship arrangement design has been through a "packaging" algorithm, Oers (2011). The application will here automatically generate a large number of feasible design configurations, combined with decision support functionality to aid in the identification of preferable solutions. A set of pre-defined modules derived from the functional specification is used as input. These modules are subsequently packed according to spatial and logical rules, and then wrapped within a suitable hull form. The primary design context is also here naval ship design, but it has been tested on other ship types as well, including offshore drill ships. A similar approach has been developed at the University of Michigan, called the Intelligent Ship Arrangement (ISA) system. This tool is intended to be used as part of the US Navy *Advanced Ship and Submarine Evaluation Tool (ASSET)*. The ISA system will capture the design rules, regulations, best practices and intent of the US Navy, quantify and compare alternative general arrangements, support the improvement and optimization of the general arrangements, and provide trade studies across a large number of possible solutions, Daniels *et al.* (2011).

The traditional software tools used in the naval architecture activities of the shipyards are obviously still active. Along those we must refer to:

Auto-Ship Systems Corporation produces a number of ship design software packages, including Auto-Ship for hull-form design, Auto-hydro for hydrostatics and stability, and Auto-structure for design of components and management of the production process. These tools act as a suite, with common data formats and interoperability. A range of parts, hull-forms and even entire ship designs are available to download from the companies' website. Auto-ship Systems also produce a cargo management tool for control of the logistics chain and cargo stowage arrangements. The tools are offered as a customized system, based on the specific user requirements.

The *NAPA group* provides a series of products and services for ship design, analysis and manufacture. They use a central ship model, which is accessed by a set of standard and add-on subsystems for analysis. The design starts with the definition of the hull-form using a Coon's patches method. The system can accommodate multi-hulls and asymmetric hulls, as well as offshore platforms. The geometry subsystem allows the design to be worked up to a detailed general arrangement. Further subsystems allow the analysis of stability in intact and damaged conditions and launching. Additional subsystems exist to analyze hydrodynamic performance, grain carriers and container ships. The latest developments in the software include a structural analysis subsystem, NAPA Steel, and on-board NAPA. The latter is intended for loading calculations and stability analysis on-board the vessel in operation.

The *MAESTRO ship structural design codes* available through DRS Technologies provide a very comprehensive preliminary ship structural design analysis capability and are used by more than 90 organizations in 23 countries. In particular, they include a ship modeling capability and limit state assessments and enable structural design of marine structures, ships, submarines, and foundations, and provide a structural optimization capability. NAPA and MAESTRO have created a NAPA/MAESTRO (2010) interface to bring more efficiency to the early stage ship structural design, analysis, and evaluation. The intent is to adopt a single product model for NAPA rather than translate it as may be required for design limit state evaluations and to create drawings suitable for classification society review and approval. This effort underlines the trend in ship design tools to adapt for commonality and facility exchange in support of enterprise life cycle data management requirements which continue to evolve.

4.1.2 CAD Systems (General Purpose and Specialized)

Throughout the history of CAD applications in the maritime industry, a special characteristic has been that the specialized shipbuilding CAD solutions have maintained a strong position. Many of the large generic CAD systems, having the ability to distribute the high development cost of new basic CAD technologies among a very large user community and across many industries, have also tried to get a foothold within the shipbuilding industry by providing shipbuilding variants of their packages. Many of those large actors have failed in this attempt. Shipbuilding CAD is a very specialized area, with a high degree of complexity and the need for a tight integration of many diverse, specialized disciplines. Those who have succeeded have typically either merged mature ship CAD functionality on top of a generic CAD/PDM system, or have integrated the shipbuilding specific functionality and process support on a very basic level. Among those CAD tools, we can refer to:

Dassault Systèmes CATIA has been used extensively in the automotive and aerospace industries. Its surface rendering capabilities have helped design a many cars and aircraft. One of their latest products is a single, open, and web-based scalable platform ENOVIA LCA PLM V6 enables real-time collaboration and online-enabled design that fully engages global collaborative innovation practices and integrates abilities for project life cycle management (PLM). It has extensive capability for the design definition of structures, distributed systems, parts management, manufacturing and specialized analysis. As a relatively new entry into the ship industry however, it has a limited user base. The preliminary design module is referred to as "Structure Functional Design" and the detail design module is named "CATIA Ship Structure Detail Design." The preliminary design module saves the model in one or many CATIA parts, and the detail design is then driven by the parts generated in the preliminary design stage, however many of the tools for ship design are still in beta form and the STEP protocol is not complete, Brennan (2011).

The *CADDS5 system* from PTC offers a full suite of capabilities for product development and manufacturing with a specific applications module related to all phases of the ship design process. All preliminary design data including hull surface, coordinate reference, seam and butt lines, frame lines, etc. are saved in a single CADDS part consisting of different layers. The detail design module is called "Advanced Structural Modeling." When doing the detail design, a user has to use the preliminary design part as a reference and create a detail structural member based on the data in the preliminary design model. The single preliminary design model and the collection of detail design models can be used for FE analysis. Surface design, outfitting, cabling, piping, advanced assembly, human product interaction as well as Enterprise collaboration capabilities are available to support ship design.

Unlike other, general-purpose CAD systems, Tribon was developed specifically for ships and provides tools that cover the entire ship design process. The *AVEVA Tribon* based system has the largest user base in the ship industry and arguably remains the world's principal ship structural design software tool. AVEVA Enterprise provides enterprise solutions for information management while AVEVA Marine provides a mature ship design capability based on the legacy Tribon system now at version M3.

ShipConstructor Software Inc. (SSI) is gaining widespread use in the ship CAD industry. Recent versions of the code have incorporated a Database Driven Relational Object Model (DDROM) technology that provides a relational-CAD capability whereby objects, through their relationships to other objects, are automatically updated to reflect modeling changes. This feature provides great utility for preliminary design since common structural changes can be quickly made and the model automatically updated through the DDROM mechanism. ShipConstructor is an AutoCAD based shipbuilding computer aided and manufacturing system that provides detail design and modeling tools for production engineering of marine structures. It enables the designer to define and generate hull forms, structures, distribution systems including piping, HVAC, ships equipment and can create production instructions for NC machinery for fabrication. It utilizes a Marine Information Model (MIM) as well as a single relational database residing on a Microsoft SQL-Server database that can export standard CAD formats including STEP, IGES and ACIS/sat.

FORAN was developed by the Spanish company SENER. A central database called the "Full-ship Product Model" is used to store the design. Spatial features within the model can be given numerical or topological links, to maintain the design style. Hull-form generation is accomplished using a Non-uniform rational basis spline (NURBS) implementation. NURBS is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces that offers great flexibility and precision for handling both analytic and freeform shapes. The software can describe mono-hull or multi-hull vessels with symmetric or asymmetric hulls. The hull-form developed can then be used for naval architectural analysis and further design work. Modules are included to estimate the hydrodynamic performance of the vessel. A notable feature of the FORAN system is the accommodation design module, which works in both 2-D and 3-D and can produce arrangement drawings for the interior fittings of the accommodation. FORAN includes modules to develop the production model, including tools to break the vessel into blocks and to draw up a build strategy. Both FORAN and Tribon now use an ORACLE database for the product model.

Graphics Research Corporations' *Paramarine* software uses the Parasolid kernel developed by EDS of Cambridge and is an object-oriented code with the user inserting and linking objects designed to assess or describe specific features of the ship design. The software is particularly suited for rapidly developing the early stages of the design definition. The use of the standard kernel allows flexibility in the defined geometry. A multi-user version of the software is under development. In addition to the extensive ship design capability, tools are under development to facilitate life-cycle management.

Intelliship, developed by the Intergraph Corporation is intended to cover the ship design process from initial design to operation. It can incorporate and evaluate the effects of distributed engineering, work sharing and lifecycle data management. Intelliship is now re-branded as Smartmarine 3D and was built using foundation based systems that are more representative of plant and processing industries than shipbuilding. Its primary marine customers are the USN and Samsung Heavy Industries in South Korea. It supports the concept of a "phase 1" geometric definition, which is represented as 3D surfaces defined by thickness rather than 3D solids. This makes the phase 1 geometric much easier to process and create global finite element meshes.

The *Nupas-Cadmatic ship design software* provides a very capable ship design package and includes features for product model interchange, development and visualization capability intended for the life cycle product management. Their ship design software was developed through a joint venture between Cadmatic Oy and Numeriek Centrum Groningen B.V. Their CAD/CAE/CAM design software is intended to improve the efficiency, design and production of shipyards and ship design offices. Their system allows for basic ship design using 3 modeling techniques and allows for complete structural design using intelligent structural topology. This method enables automatic structural component adjustment in way of hull design changes. The design model is then rapidly transformed into a production specification report complete with materials lists, panel inventory management and creation of 2D AutoCAD-like drawings for production purposes. Other modules include machinery layout, piping, outfitting, build strategy and global engineering connectivity.

A general trend for some years has been the extension of shipbuilding CAD towards integration with Product Data Management (PDM) and Product Lifecycle Management (PLM) solutions. PLM is often used to describe a comprehensive management approach to combine different perspectives with corresponding tools towards sustainable products, Nagel (2011). This may comprise Life Cycle Assessment (LCA) focusing on environmental impact, Life Cycle Costing (LCC) to assess the complete costs over the product life time, Life Cycle Performance (LCP) focusing on life cycle performance, and Cost Benefit Analysis (CBA) for decision support.

We have also seen a development towards extending the CAD model into a Virtual Reality (VR) model, Andrews and Pawling (2007); Lödding, Friedewald *et al.* (2011). This VR model can be used for design or assembly reviews, collision detection and is of particular importance for high complexity outfitting assembly. A challenge for using VR has been the model development time, given the time and resource constraints in a typical shipbuilding and engineering project, as well as handling the high number of design changes and late arrival of sub-models from suppliers. To meet these challenges, dedicated VR systems have been developed based on the specific characteristics of the shipbuilding process, Nedess *et al.* (2009). By concatenating the data imported from the CAD model with metadata derived from the PDM, PLM or ERP system, a rich VR model can be developed that allows for the interactive filtering and navigation based on ship specific model concepts rather than general geometric constructs. Further, by adding assembly sequences and manipulation logic, immersive dynamic sessions can be created.

4.1.3 Tools to Manage Inventory of Hazardous Material Data

The international convention for the "Safe and Environmentally Sound Recycling of Ships" was adopted by the IMO in Hong Kong, (2009). This convention is primarily focused on the safe and environmentally sound recycling of ships. A key requirement is the Inventory of Hazardous Material (IHM), which is also known as the ship's "Green Passport". Even though the convention is not expected to be ratified before the 2013–2015 timeframe, many shipyards and ship owners have already started to implement compliance with the convention. The last available data from IMO on IHM may be found in the Resolution MEPC 179(59) (2009).

For ships in service, the classification societies typically provide simple tools for the superintendent to support the compilation of the hazmat inventory, to serve as a basis for the verification and certification by the class. For new builds, this is typically done by the shipyard, and followed up by class throughout the construction survey process.

The tools range from simple templates to be filled out, to more comprehensive packages containing libraries of material data. One example of the latter is the PrimeShip-Inventory provided by ClassNK, centered on a large database of material declarations from ship suppliers.

4.2 Current Practice out from the Survey

This section deals with an analysis of the survey results from a tools oriented point of view. For a more comprehensive analysis of the results, please refer to chapter 8.

4.2.1 CAD Tools

AutoCAD is used by almost companies which answered the survey. This is mainly related to the exchange needs of the shipyard with providers and sub-contractors. It is obvious that AutoCAD must not be regarded as the major CAD system used in the shipyards. Depending on the design phase the usual tools remain in a dominant position. These tools include NAPA, AVEVA/TRIBON, FORAN, CATIA, and others more recent tools as RHINO.

4.2.2 Class Society Tools

Regarding the classified ships (excluding navy vessels), the answers to the survey came mainly from Europe and Asia. As expected, ABS Safehull, BV Mars 2000 and GL Poseidon, which are usually requested by ship owners, have been referred to by a large majority.

4.2.3 General Purpose Structural Analysis Tools

Three software tools have been proposed in the survey: ABAQUS, ANSYS and NASTRAN. No other tool has been proposed by the answering companies. It is noticeable that FEM tools are used in the design loop sooner and sooner. Fifteen years ago, FEA were used only during the Detailed Design Phase and often sub-contracted. Today, these calculations are made in house, and some shipyards answered that they use them even in Preliminary or Basic Design phases.

4.2.4 Computational Fluid Dynamics

Calculations with CFD tools are more confidential and still subcontracted mainly to model basin companies. This appears to be linked to the difficulty of use of such tools compared with linear FEA calculations, the need for highly specialized engineers to run the tools, and the high computational power and time requirements of the CFD tools. The shipyards in most cases are not equipped with computer platforms with the needed computation power to carry out CFD analysis in support of day-to-day design.

5 OPTIMIZATION AND DECISION SUPPORT TOOLS

Inside a comprehensive life cycle management set of tools, optimization tools are needed. Those tools play obviously a significant role during the design process but are also required during the ship operation as decision support tools to find out the best alternative for ship repair tasks.

For instance, to compare the impact of technological innovations on ship system level onto the life cycle performance in a holistic way, the European Integrated Research Project BESST, Roland *et al.* (2011) is developing a tool, which intends to compare design alternatives in view of life cycle cost, safety, environmental impact and public perception. While the focus of the tool is on complex ships build in Europe, the concept will also be applicable in other areas, e.g. to compare the environmental impact of different transport modes. At the end of the BESST project, the tool will be applied to assess the technical project results for three different "Virtual Ship Models" comprising passenger ships and ferries.

5.1 State of the Art

5.1.1 Overview of the Tools

The decision support methodology for the concept and preliminary design of complex ship structures (e.g. multi-deck, multi-hull, warships) requires hybrid solvers, multiple models and adequate computational resources. In reports of ISSC'2003 (TC IV.2), ISSC'2006 (TC IV.1 and 2) and ISSC'2009 (TC IV.1 and 2) basic definitions, models and the practical examples of progress of the profession (including aerospace) have been reported. It has showed the maturing of the design process and inclusion of decision support problems enabling designer faster and better decisions.

The modern multi-criteria, multi disciplinary design problem has to be solved as a multi-stakeholder one with the support of the ship-owner; the Classification Society/Navy and the shipyard. Besides those requirements, as mentioned in the previous Chapters, we need to include societal losses based on the risk analysis (ISSC'2009, TC IV.1) and complex economical calculations including uncertainty to cover LCC and other complex requirements. Direct calculation paradigm established in the seventies, Evans (1975), Hughes *et al.* (1980), applied the assumption that linear response models, augmented with nonlinear adequacy models are fast enough for the task. With the full introduction of the ultimate strength criteria into the design process as well as reliability based calculations (multi-point, direct), parallel processing power was needed, Thoft-Christiansen, Murotsu (1986), Zanic *et al.* (1993).

The demands today are even more stringent with introduction of e.g. collision/stranding load cases that require non-linear solvers, Paik and Melchers (2008), Hughes and Paik (2010), ALPS/HULL (2010), as well as a complex load cases definitions, Diez *et al.* (2010), complex responses for design optimization, Amatuli *et al.*

(2010), Remes *et al.* (2011) and the multiplicity of load cases as required by the new IACS CSR-H Harmonized Rules. Note that proper definition of design load cases is of paramount importance for design optimization since optimistic loads lead to unsafe structures whereas pessimistic ones lead to the inefficient structure regarding cost, weight etc. The size of the models (measured in degrees of freedom), required by those demands is also large.

However, the models can be successfully generated semi automatically (for the mesh size required for the problem at hand) through CAD to FEM interfaces in NAPA Trident, Tribon, etc. as described in Chapter 4. To handle the required large problems in the acceptable time, the techniques of surrogate (meta) modeling are used in the decision support problems. For very large problems, as well as for the integrated multi-disciplinary models, the problem decomposition and coordination techniques are often applied with or without surrogate models. Both techniques are described in the following subsections.

To handle these complex requirements in a tractable way, for the objectives defined in Chapter 3 with multiplicity of tools as defined in Chapter 4, an applicable taxonomy is needed for basic data sets, functions, associated modules and the basic optimization problems.

The design problem taxonomy, see Table 1, is defined using design descriptors and the necessary mappings from design space to the attribute space (direct or normalized) and to the selection spaces. In structural design, the mappings are implemented as computational modules for analysis (AM: response, adequacy, quality) and synthesis (SM: GUI, optimization solvers, surrogate solvers).

Those modules are integrated for solving complex problems and the design procedure flow, the design problems definitions and the generic and full ship models (example) are given in Table 2. Problems are solved via the Multi Criteria Decision Making (MCDM) techniques i.e. by its MADM or MODM variants (Problems 1A and 1B - see col. 2 of the Table 2). Filtering (Problem 2) to get non dominated solutions (Pareto frontier) is needed to enable interventions of stakeholders in subjective decision making (Problem 3).

Integration of all those modules is a complex task particularly for the large scale decomposed problems. It requires the efficient GUI and the problem sequencers for controlling the flow of data and processes. It is also important the final selection of the preferred design.

To gain the speed of the design process, the optimization process has to follow designer's data availability and provide fast answers with adjusted models. This rules out the standard optimization procedures as inoperable, and requires development of new approaches to the decision support problem for the complex ships.

Development of such novel and efficient multi step procedures is needed in order to solve the complex topology optimization problem with interwoven scantling/geometry optimization when e.g. number of decks or web frames, openings in side structure, etc., are elements of the design variables set. The general approach has to combine three design steps (see Table 2, col. 1):

Steps 1 and 2 usually use the generic/simplified concept design models (see Table 2, col. 3) for the fast generation of design variants regarding topological, geometrical and scantlings variables. The example of the concept phase optimization block is given in Table 1 for the efficient description of applied modules, surrogate modeling or decomposition techniques.

The 'full ship' model in Step 3 used for the preliminary design level optimization and analysis of the preferred design is given in Table 2, col. 3. Selection block, between two design phases, is also shown between models.

Note: RoPax ship, used here as an application example, was developed during the EU FP6 project IMPROVE and was described in the Report of ISSC'2009 TC IV.2. Novel process includes surrogate modeling with parallel processing and partial problem decomposition and is currently in phase of extensive testing, Prebeg (2011).

5.1.2 Large Scale Optimization Techniques - Surrogate Modeling,

As stated before, the analysis methods of contemporary complex engineering systems, like nonlinear CFD or FEM, can be computationally very demanding and despite of steady advances in computing power; the expense of repetitive running of analysis codes remains nontrivial. A single analysis of one design solution can take from a few minutes to hours or even much longer for e.g. non-laminar and non-stationary 3D CFD problems. Due to these characteristics, direct use of some analysis methods is not possible in optimization because the optimization algorithm may require the computation of several hundreds or even thousands of single analysis cases. An application of surrogate modeling as an approximations (or surrogates) of expensive computer analysis codes can result in significant savings in both the number of analysis and the total time in which satisfactory optimal solutions are obtained. One another important aspect of surrogate based optimization is easier parallelization of optimization process.

Surrogates also offer insight into functional relationship between design parameters and design criteria which is one of the obstacles in understanding the behavior of numerical models.

One of the most cited handbooks with detail overview of designs of experiments methods (DOE) for classical (physical) experiments is Montgomery (2001) while the overview of surrogate modeling for deterministic computer experiments (DACE - Design and analysis of computer experiments) can be found in Fang *et al.* (2006).

The main difference between "classical" and computer experiments is nonexistence of random error for deterministic computer experiments which leads to conclusion that surrogate model adequacy is determined solely by systematic bias and that the classical notions of experimental blocking, replication and randomization are irrelevant.

Steps necessary for generation of surrogate models includes: planning of experiments or sampling, execution of simulations with original analysis methods, generation or creation of selected surrogate model and validation of surrogate model adequacy.

After selecting an appropriate experimental design according to given criteria, Goel *et al.* (2008) and performing the necessary computer runs, the next step is to choose a surrogate technique and corresponding fitting method. Many alternative methods exist, and there is no clear answer which is better. The selection of appropriate surrogate method depends mostly on characteristic of physical phenomenon that is approximated.

Table 1: Basic taxonomy for integration of complex decision support models

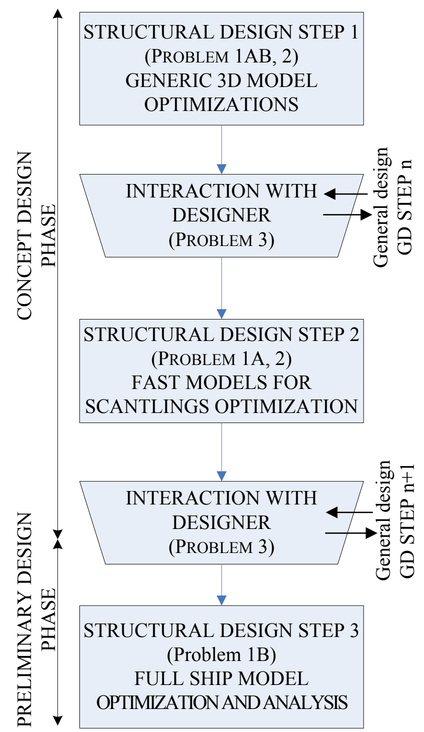
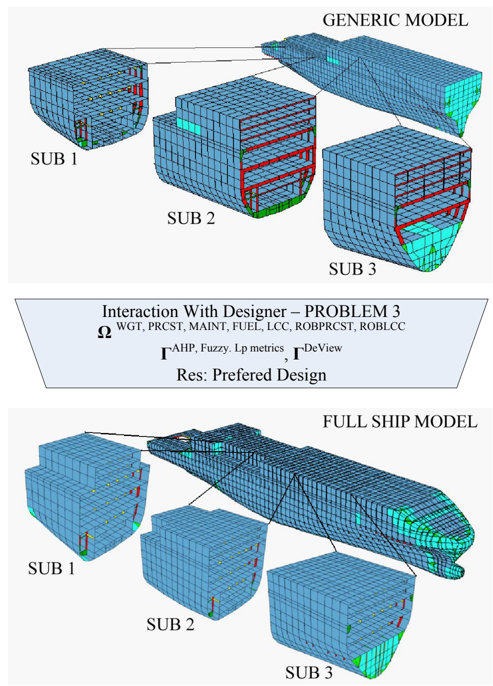
DESIGN DESCRIPTION (SETS AND SPACES)	
$\boldsymbol{d}, \boldsymbol{d}^0, \boldsymbol{d}^-$	$=$ n-tuple of (all, basic, remaining) design descriptors
$\boldsymbol{d}$	$= \{d_i\} = \boldsymbol{x}, \boldsymbol{d}^-\}; \boldsymbol{d}_i = \{d_{iMEAN}, statistics_i\}, i = 1, \ldots, n$
$\boldsymbol{D}^{\boldsymbol{k}}$	$=$ design variant k (or project $\boldsymbol{P}^k$) $= \{\boldsymbol{d}, \boldsymbol{y}, \boldsymbol{m}, \boldsymbol{l}\}^k$
$\boldsymbol{m}$	$= n_v$-tuple of normalized attribute values; point $\boldsymbol{m}^k$ in $\boldsymbol{M}$
$\boldsymbol{M}$	$=$ metric attribute space spanned by attributes m_i
$\boldsymbol{l}$	$= n_v$-tuple of composite attribute values; point $\boldsymbol{l}^k$ in $\boldsymbol{L}$
$\boldsymbol{L}$	$=$ selection space spanned by composite attributes l_i
$\boldsymbol{x}$	$= n_x$-tuple of design variables x_i, $i = 1, \ldots, n_x$; point $\boldsymbol{x}^k$ in $\boldsymbol{X}$, $\boldsymbol{x} = \{\boldsymbol{x}^{Topology}, \boldsymbol{x}^{Geometry}, \boldsymbol{x}^{Material}, \boldsymbol{x}^{Scantlings}\}$
$\boldsymbol{X}, \boldsymbol{X}^{\geq}, \boldsymbol{X}^{ND}$	$=$ design, feasible, nondomin. spaces spanned by x_i,
$\boldsymbol{y}$	$= n_y$-tuple of design attribute values; point $\boldsymbol{y}^k$ in $\boldsymbol{Y}$
$\boldsymbol{Y}$	$=$ attribute space spanned by design attributes y_i
$\boldsymbol{z}$	$=$ set of load effects (stresses, displacements from FEM response analysis) or economy data for given $\boldsymbol{d}^{\boldsymbol{\Phi}}$ and $\boldsymbol{d}^{\boldsymbol{\epsilon}}$

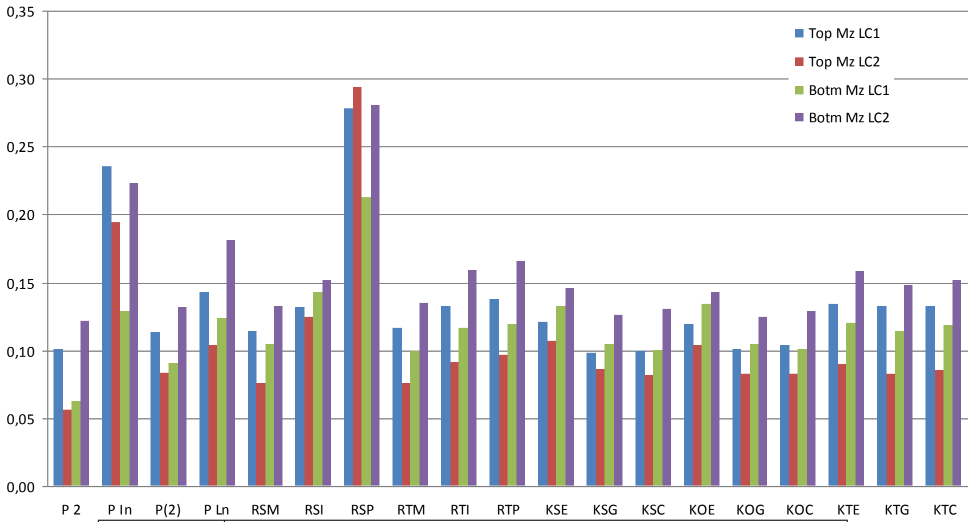
MAPPINGS	
$\boldsymbol{c}$	$= n_c$-tuple of design criteria functions (mappings) $\boldsymbol{c} = \{c_i\} = \boldsymbol{g}U\boldsymbol{a}$ $c_i : (\boldsymbol{d}, \boldsymbol{z}) \rightarrow q_i$ (quality measure)
$\boldsymbol{a}$	$= n_a$-tuple of design attributes fn's (obtained from $\boldsymbol{c}$) $a_i : (\boldsymbol{d}, \boldsymbol{z}) \rightarrow y_i$
$\boldsymbol{g}$	$= n_g$-tuple of design constraint functions(obtained from $\boldsymbol{c}$) $g_i : (\boldsymbol{d}, \boldsymbol{z}) \rightarrow I_{gi}$ (pass-fail indicator), $\boldsymbol{X}^{\geq} = \{\boldsymbol{x} \mid I_{gi} = pass, all\, i\}$; ${}_j^i\boldsymbol{H} = n_{ss}$-tuple of mappings (subsystem i to j) ${}_j^i\boldsymbol{H} : (\boldsymbol{d}, {}^i\boldsymbol{z}) \rightarrow_j^i \boldsymbol{z}(\equiv {}_j^i\boldsymbol{h})$
$\boldsymbol{o}$	$= n_o$-tuple of design objective fn's $o_i =$ manipulated/simplified a_i, u_i, l_i
$\boldsymbol{p}$	$= n_p$-tuple of probabilistically based $\boldsymbol{c}$ functions e.g. REL: $\boldsymbol{g}(\boldsymbol{d}, \boldsymbol{z}) \rightarrow p_{failure}$; ROB: $a_i(\boldsymbol{d}, \boldsymbol{z}) \rightarrow$ robustness measure
$\boldsymbol{r}$	$= n_r$-tuple of design response fn's (e.g. 3D FEM) $r_i : \boldsymbol{d} \rightarrow \boldsymbol{z}^i$
$\boldsymbol{u}$	$= n_u$-tuple of subjectively normalized attribute functions $u_i : (y_i, \boldsymbol{P}^u) \rightarrow m_i; \boldsymbol{P}^u =$ designer inter/intra attribute preference data
$\boldsymbol{v}$	$= n_v$-tuple of value functions $v_i : (\boldsymbol{m}, \boldsymbol{P}^v) \rightarrow l_i$, alternatively: $v_i(\boldsymbol{u}(ROB(\boldsymbol{a}(\boldsymbol{d}, \boldsymbol{z}), \boldsymbol{P}^u), \boldsymbol{P}^v) = l_i$; e.g. $v_i = L_p = \Sigma\lvert\boldsymbol{m}^* - \boldsymbol{m}\rvert^p)^{1/p}$ $\boldsymbol{m}^* \subseteq \boldsymbol{D}^{target}$ or $\boldsymbol{m}^{ideal} = \boldsymbol{m}^* = \{m_i^{max}\}$

COMPUTATION MODULES AND THEIR APPLICATION TO DECISION SUPPORT PROBLEM	
$\boldsymbol{\alpha}$	$=$ adequacy meta-system; subset of modules in the analysis model (AM) containing safety (e.g. class. Rules) constraint functions/mappings g_i. Output: $\boldsymbol{I}_{gi}$, $\boldsymbol{g}$-values.
$\boldsymbol{\Gamma}$	$=$ set of synthesis modules (GUI) in synthesis model (SM) for optimization (using $\boldsymbol{P}^u$,$\boldsymbol{P}^v$ data for subjective definition of $\boldsymbol{u}$ and $\boldsymbol{v}$), designer interaction with the design process, filtering of designs and visualization of $\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{M}, \boldsymbol{L}$ spaces. Output: $\boldsymbol{m}, \boldsymbol{l}$.
$\boldsymbol{\Delta}$	$=$ set of modules for the synthesis (optimization) problem definition (selection of variables $\boldsymbol{x}$ and criteria fn's $\boldsymbol{a}$ and $\boldsymbol{g}$, problem decomposition and coordination)
$\boldsymbol{\epsilon}$	$=$ environment/economy meta-system (loads, costs, etc.); subset of modules in AM with data generators E: $\boldsymbol{d}^{\boldsymbol{\epsilon}} = \{\boldsymbol{d}^{pressuresLC}, \boldsymbol{d}^{accelerationsLC}, \boldsymbol{d}^{masses}, \boldsymbol{d}^{costs}\} = E(\boldsymbol{d}^0) \subseteq \boldsymbol{d}$
$\boldsymbol{\Phi}$	$=$ structural (physical) meta-system; subset of modules/modelers in AM/SM with data generators F: $\boldsymbol{d}^{\boldsymbol{\Phi}} = \{\boldsymbol{d}^{topology}, \boldsymbol{d}^{geometry}, \boldsymbol{d}^{material}, \boldsymbol{d}^{scantlings}\} = F(\boldsymbol{d}^0) \subseteq \boldsymbol{d}$
$\boldsymbol{\pi}$	$=$ reliability/robustness meta-system; subset of AM containing modules based on **REL/ROB** ($\boldsymbol{d}_{MEAN}, \boldsymbol{statistics}, \boldsymbol{z}$) functions. Output: $\text{prob}_{\text{failure}}$, robustness measures
$\boldsymbol{\rho}$	$=$ response meta-system; subset of AM, containing modules for FEM procedures r_i. Output: $\boldsymbol{z}$ (load effects).
$\boldsymbol{\Sigma}$	$=$ set of optimization solvers (e.g. Seq. Linear Programming- (SLP), Fractional Factorial Experiments (FFE), Multi Objective Particle Swarm Optimization (MOPSO), Multi Objective Genetic Algorithms (MOGA), Evolution Strategy-Adaptive Monte Carlo (ES - AMC), etc.) generating Pareto frontier $\{\boldsymbol{x}^k, \boldsymbol{y}^k\}^{ND}$ by filtering designs in $\boldsymbol{X}^{\geq}U\boldsymbol{Y}^{\geq}$ based on objectives $\boldsymbol{o}$.
$\boldsymbol{\Xi}$	$=$ surrogate solvers (e.g. Response surfaces (RS), Kriging, Radial Basis Functions (RBF), etc.) Input : set $(\boldsymbol{d}, \boldsymbol{z})^k$ from fn c_i, output: quality measure q_i for any $\boldsymbol{d}, \boldsymbol{z}$; e.g. $q^{RBF} = c_i^{RBF}(\boldsymbol{d}, \boldsymbol{z})$, $(q^{RBF} \equiv y_i, m_i, l_i$ or $z_i)$
$\boldsymbol{\Omega}$	$=$ design uality meta-system; subset of AM/SM containing functions/mappings a_i. Output: $\boldsymbol{y}$.

Example of Optimization PROBLEM 1A, 1B, 2	
$\boldsymbol{x}$	$\boldsymbol{x}^G = F(\boldsymbol{d}^{0G}), \boldsymbol{x}^T = F(\boldsymbol{d}^{0T}), \boldsymbol{x}^S = F(\boldsymbol{d}^{0S})$
$\boldsymbol{y}$	$\boldsymbol{\Omega}^{cost}, \boldsymbol{\Omega}^{mass}, \boldsymbol{\Omega}^{VCG}$
$\boldsymbol{g}$	$\boldsymbol{I}_g = \alpha^{BV} (= \alpha^{MAESTRO})$
$\boldsymbol{AM}$	$\boldsymbol{d}^{\epsilon} = E(\boldsymbol{d}^{BV\,Loads}), \rho^{MAESTRO}$
$\boldsymbol{SM}$	(a) $\sum^{DOE,\,ANOVA}(x^T, x^G)$, (b) $\sum^{MAESTROSLP}(x^S)$
$\boldsymbol{Res}$	6 Topological/Geometrical Variants

Table 2: Large scale design procedure

DESIGN PROCESS PHASES	DECISION SUPPORT PROBLEMS	MODELS AND SELECTION BLOCK
	PROBLEM 1A - Multi Attribute Decision Making (MADM) solution. Solved by $\boldsymbol{\Sigma}$ optimizers (may include surrogate solvers $\boldsymbol{\Xi}$). Generate set of designs $\boldsymbol{y}^k = \{\boldsymbol{a}(\boldsymbol{x}^k, \boldsymbol{d}^-), \boldsymbol{p}\ (\boldsymbol{a}(\boldsymbol{x}^k, \boldsymbol{d}^-))\}$ for $\boldsymbol{x} \in \boldsymbol{X}^{\geq}$ PROBLEM 1B - Multi Objective Decision Making (MODM) solution. Solved by $\boldsymbol{\Sigma}$ optimizers (including surrogate solvers $\boldsymbol{\Xi}$). Extremize $y_i = \{a_i(\boldsymbol{x}, \boldsymbol{d}^-), \boldsymbol{p}(a_i(\boldsymbol{x}, \boldsymbol{d}^-))\}$ for $\boldsymbol{x} \in \boldsymbol{X}^{\geq}$ Extremize $l_i = v_i\ (\boldsymbol{u}\ (\mathrm{ROB}\ (\boldsymbol{a}(\boldsymbol{d}, \boldsymbol{z}), \boldsymbol{P}^u), \ \boldsymbol{P}^v)$ for $\boldsymbol{x} \in \boldsymbol{X}^{\geq}$ PROBLEM 2 - Using $\boldsymbol{\Sigma}$ modules filter the nondominated (Pareto) solutions $\boldsymbol{D}^{\mathrm{kND}}$, from designs generated in PROBLEM 1, based on direction of quality improvement for each objective. Appl. as second part of MADM or for multiple MODM runs. PROBLEM 3 - Using $\boldsymbol{\Gamma}$ modules select the preferred design $\boldsymbol{D}^{\mathrm{FIN}}$ on Pareto frontier (PROBLEM 2). Apply: (1) normalized attribute functions set $\boldsymbol{u} = \{u_i\} = \{w_i\ (\boldsymbol{P}^{\mathrm{u\ AHP}}) \cdot U_i(y_i, \boldsymbol{P}^{\mathrm{u\ fuzzy}})\}$ enables mapping of $\boldsymbol{y}$ to normalized values $\boldsymbol{m}$ using: • inter-attribute preferences $\boldsymbol{P}^{\mathrm{u\ fuzzy}}$, defined interactively, containing coefficients of each fuzzy function U_i. • intra-attribute subjective preference matrix $\boldsymbol{P}^{\mathrm{u\ AHP}}$, defined interactively, that allows calculation of the importance factors $\mathrm{w} = \{\mathrm{w}_i\}\|\boldsymbol{\Lambda}\|$, ($\boldsymbol{\Lambda}$ is an eigenvector corresponding to the largest eigenvalue of the problem ($\boldsymbol{P}^{\mathrm{u\ AHP}}$ - $\boldsymbol{\lambda}$ I) w = 0). (2) subjective value of each design defined using functions $\boldsymbol{v}$ ($\boldsymbol{m}^k$) for the design variant k based on e.g. distance norms $\boldsymbol{v} = \{L_p\}$, p=1,2 or ∞; used with respect to the specified target design $\boldsymbol{m}$*.	



Abbrev.	Description
P2	Full second order polynomial surrogate
PIn	Polynomial with interactions
P(2)	Pure quadratic polynomial surrogate
PLn	Linear polynomial surrogate
RSM	Simple RBF, Multiquadratic basis function
RSI	Simple RBF, Inverse multiquadratic basis function
RSP	Simple RBF, Thin plate spline basis function
RTM	Trend RBF, Multiquadratic basis function
RTI	Trend RBF, Inverse multiquadratic basis function
RTP	Trend RBF, Thin plate spline basis function
KSE	Simple Kriging, Exponential variogram model
KSG	Simple Kriging, Gauss variogram model
KSC	Simple Kriging, Cauchy variogram model
KOE	Ordinary Kriging, Exponential variogram model
KOG	Ordinary Kriging, Gauss variogram model
KOC	Ordinary Kriging, Cauchy variogram model
KTE	Trend Kriging, Exponential variogram model
KTG	Trend Kriging, Gauss variogram model
KTC	Trend Kriging, Cauchy variogram model

Figure 1: Normalised RMS error for the tested surrogate models for the girder bending moment in top (deck) and bottom of the barge structure for two load cases - sag, hog (Prebeg, 2011)

Probably the most widely used surrogate method are response surfaces (RS) that approximates criteria functions using low order polynomials, mostly simple linear and quadratic or some specific polynomials like orthogonal Legendre polynomials. RS' popularity for modeling of deterministic computer experiments, besides their good characteristics for certain type of problems, is due to the fact that surrogate modeling itself evolves from classical Design of Experiments theory where RS was used for the description of physical phenomena. Some of the applications in engineering includes: ship structural optimization, Prebeg (2011) and Pareto front generation, Goel *et al.* (2007).

Another surrogate modeling method that evolves from statistics, in this case geo-statistics, is Kriging modeling which was originally developed to estimate mineral concentrations over an area of interest given a set of sampled sites from the area. A Kriging model is a generalized linear regression model that accounts for the correlation in the residuals between the regression model and the observations. Kriging offers a good flexibility to approximate many different and complex response functions and it is a good choice for approximating deterministic computer models because it interpolates the observed data points. Kriging models have been used in a variety of applications including conceptual design, structural optimization, multidisciplinary design optimization, aerospace engineering and mechanical engineering.

Radial basis functions (RBF) (surrogate method) have been developed for scattered multivariate data interpolation. The method uses linear combinations of a radially symmetric function based on Euclidean distance or other such metric to approximate response functions. Like Kriging, it is also interpolation based technique and it is a good choice for approximating deterministic computer models. Other surrogate models used in engineering includes: Artificial Neural Network (ANN), Support Vector Machine (SVM), Splines (linear, cubic, NURBS), Multivariate Adaptive Regression Splines (MARS). Comparison of different surrogate models for girders in a barge structure is presented in Fig. 1 based on Normalized RMS error measure.

5.1.3 Large Scale Optimization Techniques - Decomposition and Coordination

Complex engineering systems can typically be considered a hierarchy of coupled subsystems. The total performance of such complex systems is a combination of responses evaluated at each of subsystems. A standard optimization approach that does not take into account this behavior usually treats the total system, or some part of the total system, as one integral element with one optimization sub problem. Another approach is to treat the total design problem as a group of non-coupled optimization sub-problems with their local objectives, not taking into account the influence that such changes have on the overall design, while system design objectives are not translated into subsystems/sub-problems criteria.

As stated in the overview by de Wit and van Keulen (2010), the field of multi-level optimization and multi-disciplinary optimization is concerned with developing efficient analysis and optimization techniques for complex systems that are made up of coupled subsystems (components). Multi-level or multi-disciplinary optimization methods rely on a decomposition of the optimization problem into individual optimization problems that are coupled. Thus, it is attempted to incorporate design variables, objectives and constraints originating from different levels and/or disciplines into the design.

Unlike some other overviews that handled either multi-level optimization or multi-disciplinary optimization, de Wit and van Keulen (2010) focuses on the general steps of methods that belong to either the field of multi-level optimization or the field of multi-disciplinary optimization. According to that work the coordination approaches that handle decomposed problems can be classified according to the Figure 2.

Some of the existing coordination methods includes: Optimization by Linear Decomposition (OLD), Concurrent Subspace Optimization (CSSO), Linearized multi-level optimization (LMLO), Collaborative Optimization (CO), Bi-level Integrated Systems Synthesis (BLISS), Analytical Target Cascading (ATC), Analytical Target Cascading with Lagrangian Coordination (ALC), Quaziseparable Decomposition (QSD), and Inexact Penalty Decomposition (IPD).

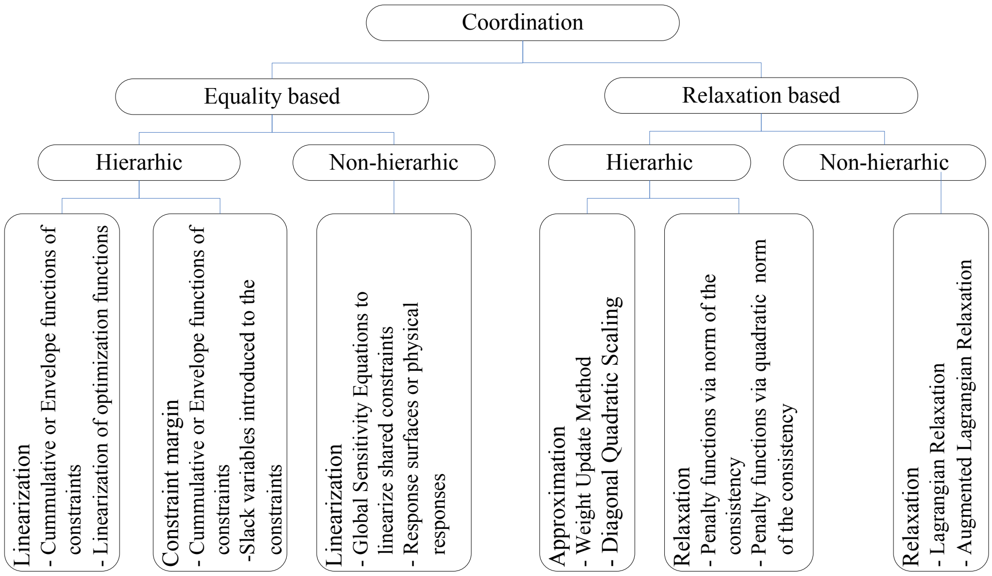


Figure 2: Classification of coordination approaches

Several basic properties for some of the mentioned multilevel optimization methods are given in Table 3 based on Agte *et al.* (2010).

Flowchart of BLISS, based on Agte, (2005), is given in Figure 3 as an example of tool that includes multilevel optimization in combination with surrogate modeling and selection of appropriate surrogate modeling technique with respect to the relevant accuracy criteria.

In one of the recent panel discussions from this research area, Agte *et al.* (2010) two perspective directions or categories for future advancements has been identified.

The first category, so called horizontal, encompasses developments that improve on the capabilities already established toward greater dimensionalities of the applications and extend the application spectrum, e.g., to include the life cycle, economic factors, uncertainty, and reliability.

The second category, or so called vertical, identify developments that are conceptually and qualitatively new, for instance optimization of entire families of products for cumulative return on investment. The two orthogonal growth directions are expected to symbiotically reinforce each other into a "dream growth" delivering capabilities that are both qualitatively new and powerful in terms of the size of the problems they will solve.

Table 3: Overview of basic aspects of multilevel optimization methods

	CO	CSSO	BLISS	ATC
System-level analysis required	×	✓	×	×
Subspace sensitivity analysis required	×	✓	×	×
Number of levels	2	2	2	2+
Subspace optimization influenced by targets	✓	×	✓ (indirectly)	✓
Autonomous subspace optimizations	✓	✓	✓	✓

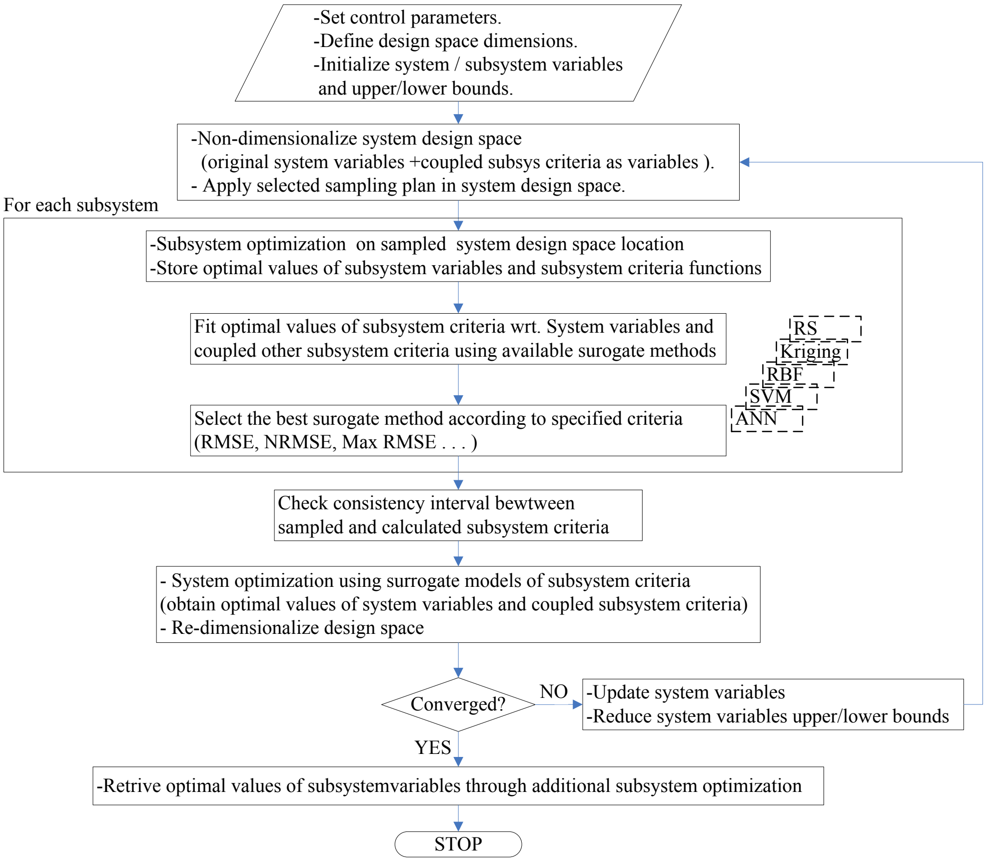


Figure 3: Flow chart of BLISS - multi-level optimization method with surrogate modeling used for subsystems

5.2 Current Practice and Future Trends

5.2.1 Optimization for Design and Production

Classical design paradigm: 'cost vs. safety in the available time' is also in the background of the modern design procedures. One of the major drivers of expected achievements are novel design methodologies that have to closely join two collaborating design systems (general ship design and structural design) as well as the basic stakeholders in the paradigm (Owner, Yard/Designers, Regulatory institutions) through formulation of Decision Support Problem for rational decision making. Multi-stakeholder approaches achieved through an interactive design environment (GUI) enables stakeholders to discover their subjective preferences and may improve the quality of decisions. It was confirmed in the EU FP6 projects IMPROVE and DeLight that the primary role structural designers is to generate a Pareto frontier of non-dominated structural designs. This frontier is then used for higher level decision making (general design) to multiply the benefits from the structural optimization.

Ship-owner's profit can be significantly increased due to reduction in fuel consumption (better propulsion and ship hull form, reduced weight, etc.), increase in payload and better LCC performance. It is also very important to acknowledge that reduction of fuel consumption can significantly reduce CO2 emission, thus increasing environmental friendliness and also ensuring that requirements related to the pollution would be easier satisfied in the foreseeable future.

Regarding cost competitiveness, the new methodologies give shipyards and owners the possibility to select competitive design solutions by following the paradigm: better ship for the shipyard production and more profitable ship for the owner. Modern designs presented in many recent papers and the associated design attribute values prove that gains from this paradigm, as well as the efficiency of the modern methodology (design and IT), is driving the design process towards such optimization approaches.

Hamada *et al.* (2011) propose a new design system discussing uncertainties in the product information. The system newly, introducing an optimization method named Wildcard GA, has been applied at the initial design stage whose decisions extremely influence the cost and performance, and when the detailed information on the ship is not available. From the viewpoints of optimization and convergence of solutions, superior performance by Wildcard GA compared to general optimization methods is also reported.

Nakamori *et al.* (2010) report an optimal structural design of midship sections with rearrangement of compartments and investigate the influence of the design variables in the structural optimization of the midship sections of bulk carries showing the material and assembling costs of the optimized structural design by using their own developed structural optimal structural design system with a genetic algorithm. The developed system is connected with the 3D product model.

The features of the tool and the related methodology, as well as the Key Performance Indicators used to do the assessment is described in more detail by Nagel (2011ab).

Regarding safety: In the Proceedings of ISSC, 2009, TC IV.1, Section on 'Defining the principles for acceptance criteria', the owner's and societal interests are contrasted. Owner's basic economical consideration (y) can be, somewhat simplified, summarized as:

$$
\begin{array}{llcl}
\text{y} = & \text{net gain with running costs subtracted} & - & \text{sum of calculated expected loses i.e. risks} \\
 & & \text{or} & \\
\text{y} = & \text{(p)} & - & \text{(r)}
\end{array}
$$

with y > 0, where the second term r represents the sum of N considered unwanted events, quantified by product of i-th event frequency ($\boldsymbol{\lambda}_i$) and the associated expected loss for the owner. Note that r can be subdivided into risks related to serviceability ($\mathrm{r}_{\mathrm{service}}$) and collapse ($\mathrm{r}_{\mathrm{ultimate}}$) criteria due to different associated costs, related to maintenance and loss of ship respectively. The inequality can be applied for any time horizon, and corrected for the related ship condition, interest rates, etc. that the owner considers applicable for his vessel.

The owner should provide added value to society (GBS/Tier 0) and assure that activity is the corporate-socially responsible, Ditlevsen (2004). This constraint can be expressed as:

$$
\begin{array}{rcl}
\text{y} \cdot \text{(societal factor (fraction) signifying the part to be asset to society)} & > & \text{(sum of societal risks)} \\
 & \text{or} & \\
\text{y} \cdot \text{(t)} & > & \text{(s)}
\end{array}
$$

where the right hand side term represents the sum of N considered unwanted events, quantified by product of the event frequency and expected loss for the society in excess of owner's compensation and his own loss.

Therefore, the implementation of social responsibility constraint in the owner's considerations is a process taking place at IMO, possibly leading to new ship designs, that meets the new technological demands.

This contemporary philosophy certainly leads towards better ships of the future, although the data for societal constraint is hard to obtain and may require specific country dependent considerations. It still gives a clear direction of societal objectives that will be enforced in the future. Since ships are products with a long lifespan, a realistic design approach that will be in line with the foreseeable societal responsibilities, is needed now.

However, to be implemented in practice, the procedure has to be followed by the practically applicable method leading in the same direction but free, if possible, of dubious considerations.

After problem identification, the Decision Support Package (DSP) problems are usually manipulated into a mathematically equivalent formulation but solvable within the available solution strategies and accompanying techniques.

It is obvious that the problem may be, in general, manipulated into at least three formats: In the first format the owner's gain is maximized along the different (dependent on i) acceptable risk (or λ_i) contours. In the second format the risk is minimized along the different acceptable owner's gain contours. The third formulation will produce the Pareto frontier of non-dominated designs making DSP transparent and suitable for techniques of subjective decision making by the stakeholders (owner, yard, regulatory organizations). The mathematical requirement is that the order of designs regarding the applied quality measure is maintained i.e. the monotony of both: the simplified measure of design quality and the full formulation.

If (s) and (r) can be replaced with the simplified deterministic or robustness safety measures, the selection of quality designs will be largely simplified related to the largely philosophical ISSC TC proposal. In the third problem, the definition is still entangled with disputable parameters such as cost of life, etc. Those considerations are excluded from the Blocks for generation of the Pareto frontier (see Table 2) and transferred to the Blocks for selection of the preferred design on the generated hyper surface of no dominated designs.

It is only now that complex requirement, given before as $(p(x,d) - r(x,\lambda,d)) \cdot t > s(x,\lambda,d)$, has to be included, but only as a filter on the small set of generated Pareto designs. Subjective considerations still lie with the stakeholders (designer, owner, society, politics, etc.) but they are applied to the specified Pareto designs. It seems to be a substantial step forward in the inclusion of safety in the design process, at least in selecting the design with required gain but with simultaneously maximized safety or the safest design for the required/selected gain - see Thoft-Christiansen and Murotsu (1986), Zanic *et al.* (2010). Basic conclusion is that we are required to include safety considerations, not only as design constraints but also as a design goal if we want the maximum gain for the given investment from the owners' and societal point of view.

For those reasons, the research and applications area is currently very active and some recent references on the related topics are provided in this paragraph:

Recent methodology is presented in Cui *et al.* (2008), Fach *et al.* (2009), Gillespie *et al.* (2010), Tosserams *et al.* (2010) with interesting approach to metrics in Caprace *et al.* (2010).

Ship general design is given in Vasconcellos (2010), Clauss *et al.* (2010), Balmat *et al.* (2009), while conceptual structural design is discussed in Amrane *et al.* (2011), Andric *et al.* (2010). Detail design problems are presented in Zimmermann *et al.* (2009), Frank *et al.* (2010).

Reliability related methods are presented in numerous works e.g. Wang *et al.* (2010), Kawamura *et al.* (2010), Rizzuto *et al.* (2010), Balmat *et al.* (2011), Okasha *et al.* (2010), Gang *et al.* (2011) with loads prediction in Eisen *et al.* (2009).

5.2.2 Optimization for Operation

Since synthesis methods and modules for the decision support problems are domain independent, (if analytical model is available) the methodology is applicable also in the optimal operations area. Some recent references on the related topics are given in the sequel:

Onboard operations are presented in Perera *et al.* (2011) where the prototype of an onboard decision support system for ship navigation under rough sea and weather conditions is under development (implemented on the Ro-Ro ship). For calibration and validation, the system is currently collecting data (motions, strains) as the ship operates. The time series of the values of the strains at these sensors locations, are supposed to serve as the basis for training of a neural network, capable of quickly and accurately giving the expected loads at the present sea state and also the possible ship's courses and speeds.

Routing and operations based ship design is given in Eljardt *et al.* (2009) where a new approach to benchmark different designs, keeping a clear focus on the operation is presented. It has proved that it is possible to simulate a complete lifecycle of a projected vessel, using fore- and hind casted operation data (ship-specific and environmental). The use of an entire maneuvering simulation leads to a complete database of operational data. Using simulation it is possible to evaluate and optimize the design regarding operational efficiency, rudder design and also ship safety. In addition it is possible to reliably measure the savings/expenditures of design on a lifetime basis.

The paper by Egorov *et al.* (2010) presents the analysis models and criteria for two new Russian multipurpose Emergency Rescue and Response vessels (MPV) concepts, i.e. salvage vessel with icebreaker/high ice class functions. Complex combination of vessel's functions brings to mutually contradictory tendencies while defining hull forms, main particulars and other MPV properties, opening a stage for the multicriterial decision making.

The paper by Dolinskaya *et al.* (2009) presents the investigation of the optimal short-range routing of a vessel in a stationary random seaway. To obtain the fastest path between two points, the underlying structure and properties of the maximum mean attainable speed are analyzed. While the presented analysis is restricted to finding a path that minimizes the total travel time, the same results are valid for other path-optimizing problems e.g. finding a path minimizing the fuel consumption of a vessel, etc.

Energy efficiency is treated in the paper by Boulougouris *et al.* (2009) urging for the collaboration of all major stakeholders of shipbuilding and ship operations to efficiently address this complex techno-economical and highly political problem. Coordination of efforts of many maritime stakeholders, with often conflicting interests, and ultimately aiming at optimal ship design and operation solutions has been addressed within a methodology developed in the recently completed EU-funded project LOGBASED (Logistics-Based Design Procedure). Based on the knowledge base developed within this project, a new parametric design software tool (PDT) has been developed for implementing an Energy Efficiency Design and Management Procedure as the part of an earlier developed Holistic Ship Design Optimization Approach. It addresses the multi-objective ship design optimization problem. It provides Pareto-optimum solutions and a complete mapping of the design space in a comprehensive way for the final assessment and decision by all involved stakeholders.

Risk assessment is presented in Kaneko *et al.* (2009) for determination of the ship's global fatality risk level and environmental global risk level. They were obtained based on the estimation of number of regional collision hazards applied to a specific sea area. From the estimated number of collision hazards and the corresponding number of collision accidents, the collision avoidance failure probability was estimated. Since it represents a fundamental characteristic of a trained mariner, this value would be almost unique all over the world, making it possible to estimate collision frequency/ regional environmental risk of any sea area where observed data of ships' movement are available. It is also possible to estimate the regional risk of a ship which sails in only specific sea areas and to consider the effective safety measures for such ships.

6 PRODUCT LIFECYCLE DATA MANAGEMENT

Product lifecycle data management refers to the manner in which data is managed by shipbuilding projects that are following a recent trend towards adopting Product Lifecycle Management, or PLM methods for their business operations. This process is intended to manage the engineering development of products from cradle to grave and includes concept formulation, design development, manufacture, release into service, in-service maintenance, and disposal. This process is distinct from Product Life Cycle Management (PLCM), which refers to the management of product marketing in the commercial sense. The importance of a PLM-driven, extended enterprise platform is nowhere more apparent than in the shipbuilding industry. Appropriate implementation of PLM is expected to automate every aspect of a ship's entire lifespan and includes everything from configuration management through quality control and service. The fast-paced innovation required for naval and other leading edge shipbuilding projects can be better realized by streamlining its processes and managing product data in a controlled environment. Such a capability is intended to help shipyards improve productivity across a global network of suppliers and efficiently respond to a rapid design development. Appropriate product lifecycle data management will provide a seamless technology platform and enable optimizing the total enterprise performance throughout design development, production, and during the entire in-service phase of a ship or class.

In addition to the technical difficulty of the data management, obstacles towards a more integrated use of data and information throughout the life cycle phases include the management of IPR and aspects of work organizations and cooperation between the different stakeholders in the life cycle. The European project THROUGHLIFE (2011) is aiming to identify obstacles and potentials of a closer cooperation between new building yards, repair yards and ship owners. Based on this, the project is intending to develop innovative business models to facilitate closer cooperation of stake holders on one side, and innovative technical solutions with a higher reliability and more efficiency over the entire life cycle. The technical developments of the project will focus on alternative means to achieve structural durability: innovative means of corrosion protection versus the use of anti corrosive steels and composite materials.

6.1 State of the Art

A key factor in PLM is the need to define the product. The ship building industry has been developing specific Ship Product Models[1] (SPM) to support the design, analysis, construction, and management of commercial and naval vessels for nearly a decade, Brennan *et al.* (2011). SPMs facilitate unification of 3D CAD data models that incorporate hull structure, propulsion, steering, distributed systems such as piping, electrical, and HVAC, as well as all other components that allow defining an entire ship using a single database. Ship classification societies and navies, most notably the United States Navy's LPD 17 and DDG 1000 projects, continue to develop and apply efforts to bring SPM technology to its full potential.

For an SPM to be useful it must facilitate seamless data transfer between the various groups that require access to support the product at some stage in its lifecycle. While a specific single data standard remains to emerge, NAVSEAINST 9040.3 outlines the policy for ship design data exchange in United States Naval construction projects. The ISO 10303 standard outlines a methodology for model definition to enable data exchange. The LPD 17 project, which started in 1994, was the first United States Naval program to use such an Integrated Product and Process Development (IPPD), Keane *et al.* (2009). The IPPD process led the LPD 17 design towards improved producibility and helped integrate the government project design teams with industry and production. It provided a collaborative strategic infrastructure embodying data standards that supported the project business across geographically dispersed and heterogeneous organizations with the ability to electronically access, share, process, and analyze data throughout the program and its anticipated complete life cycle. The seamless environment linked the acquisition and logistics program teams and allowed single entry, manipulation, configuration management, maintenance and approvals processes and ultimately facilitated management, administration and program execution efforts.

Improved automation of computer aided design and engineering activity was needed to develop a ship product model (SPM) that could support appropriate data transfer and facilitate integration of engineering with production. A significant adjustment of mind-set was required but the efforts to enable extensive concurrent engineering activity ultimately allowed a robust product data management (PDM) capability. The modeling and simulation tools used by the IPPD needed features that enabled access by the various project operations using a distributed network design to provide necessary details of ship systems including auxiliaries, propulsion, electrical and ship structure as well as signature management and other capabilities. The development of an integrated product data exchange (IPDE) capability allowed the LPD 17 project to use a wide area network (WAN) that enabled effective data exchange across some 20 sites and could support up to 250 users.

The Canadian Navy has also sponsored development of an SPM based computer-aided ship data and analysis capability to improve the Life Cycle Management of its fleet during this same period. Much of this work was progressed by Martec Ltd., Brennan *et al.* (2011) who developed the Improved Ship Structures Maintenance Management (ISSMM) Technical Data Package (TDP) under contract to Defense Research

[1]SPM is used in the literature to refer to ship product model, smart product model and single product model. In most cases the meanings are synonymous

and Development Canada (DRDC). They successfully demonstrated the feasibility and utility of an SPM concept by using the CAD-like database of the Canadian Navy's FFX330 class to perform integrated sea load and structural analysis and to determine the effects of structural damage on a vessel's ability to undertake intended operations. The ISSMM project and others in the Canadian system use the navy's Structural Inspection Database (SID) as well as the TRIDENT finite element analysis and modeling system. Various application interfaces (API) through the TRIDENT graphical user interface enable performing a complete set of ship design and analysis functions that, among other capabilities, provide an extensive set of software tools that address structural Life Cycle Management (LCM) issues. It is reasonable to expect that future Canadian naval vessels will be designed and built using SPMs.

There exists a strong global interest by ship owners, design agencies, and SPM software producers to extend their applications beyond design and construction and to apply Life Cycle Data Management (LCDM) techniques into shipbuilding projects. This integrated process is expected to avoid the time consuming and costly practice of producing individual models and analyses that need to be translated or otherwise revised to support the numerous activities and practices required for other in-service maintenance management requirements for naval ships, or maintaining classification for commercial ships. An effective capability is also expected to speed up design, design change, production definition and materials procurement and production. Earlier and more thorough access to the design process by all concerned parties will not only reduce project costs by shortening the development phase but also the time required to reach market and will allow an improved understanding of vessel, its systems and ultimately improve confidence in the vessels performance and its safety.

Liu and Zhang (2009) examined the computer aided design capability of Chinese shipbuilding and explain how important it is for Chinese shipbuilding, in way of the global financial crisis to take advantage of modern CAD/CAM technology to transform their philosophy and methodology to better consolidate their position in worldwide competition. The need for integrated hull, outfitting and integrated design and manufacture is vital and they recommend establishing integrated digital shipbuilding platform based on the PLM system to apply open CAD for the upstream design tool with the manufacturing process management (MPM) software system as the downstream, tool. They point out that ship design software is difficult to apply for Chinese shipbuilding unless it includes Chinese characters. They consider that adopting this technology will help speed up their process and facilitate improved high technology content for ship designs.

While LCDM techniques have achieved expectations in practice by the aerospace and automotive industries, a full-fledged implementation of LCDM remains under development as an emerging capability throughout most of the shipbuilding industry. In summary, LCDM requires a thorough review and understanding of the ship product business process, including all aspects of management, engineering, procurement, fabrication, quality control, distribution, and in-service support activity. Once the process is mapped, an optimization of each element is necessary to develop effective and appropriate standard operating procedures and to ensure that all program stake holders are able to fulfill their mandates efficiently. In some cases a reorganization of mandates or processes may be necessary. Following process optimization, a data access and retrieval method must be established, implemented, and maintained. Periodic reviews of the system and its efficiency will then be required to update and facilitate knowledge transfer as well as allow for back-use or re-application of pertinent legacy information for future products. A particular difficulty remains with the means required to resolve the technical problem of data access and exchange. Many of the engineering design and analysis methods used for ship design evolved from unique sets of technology and tend not to share common formats, models, data structures, or methods for exchange. The review of recent literature in this filed offered in this chapter provide practical examples and reinforce many of these concepts.

6.1.1 Design for Life Cycle

As already introduced, cost is always an important issue in ship operation, which encompasses the entire product life from conception to disposal. Manufacturers usually consider only how to reduce the cost of materials acquisition, production, and logistics. In order to survive in the competitive market environment, manufacturers now have to consider reducing the cost of the entire life cycle of a product, called LCC, Hansen (2003).

Design improvement such that maintenance is easier and that ship problems are less frequent or less significant may certainly reduce the cost of exploitation and increase safety. Currently, the LCC is not yet the major concern for shipyards. This is an economic and strategic mistake. Integration of the LCC, including maintenance costs and operating costs in the design procedure, could be used by designers and shipyards as a huge selling argument. If the shipyard can show to the ship-owner that the proposed design satisfies the standard technical requirements and the usual ship-owner specifications but also considers maintenance and operation issues, the shipyard may get the order even if its offer is not the cheapest. Ship-owners want to minimize short term investment but above all maximize their profits. Some new solutions are currently in development, Nagel (2011), Renard (2009), Sharma (2010).

More considerations about Life Cycle Management are considered in chapter 2.

6.1.2 Overview of the LCDM

Lee *et al.* (2006) describe the overall structure and basic requirements for a typical ship product based life-cycle technical information management system. Their particular system was developed to evolve isolated engineering workstation based design, production, and management methods into a system that allowed full process collaboration between distributed groups of experts. This evolution is considered an essential step towards a more efficient shipbuilding product development and maintenance process. They analyzed ship design and build practice using the integrated computer-aided manufacturing language (ICAM) and integrated definition (IDEF) methodology, first introduced by Mayer *et al.* (1995). They then established an integrated system framework definition using the Unified Modeling Language (UML) to integrate applications and database functions within a concurrent engineering environment. They defined the Integrated Data Environment (IDE) capability to be the end goal of a continuous acquisition and life-cycle support (CALS) system implementation and explained how it relies on sharing information between servers and clients over a local or wide area network. Security management of such data is possible using various means such as privilege control and public key infrastructure (PKI) methods as well as more secure Military systems. A typical system combines various databases in a manner that allows users to access single product models and perform analyses, develop solutions, or establish production or maintenance activity.

A ship technical information management system must hence include a framework for development and application of a diverse set of necessary tools. It must provide the design support system and allow for document management. It must include project management and deal with knowledge management. Access and process requirements for these systems differ and must take into account the need for through life systematic and integrated management.

The requirements to build a common data model for total ship lifecycle data management were defined by Thomson (2010). He divided the ship lifecycle into five distinct phases that include the initial concept definition of a ship; the detail engineering and procurement phases of major equipment; the exchange of data with classification societies; development of design and production documentation and the final handover and operation phase. Each phase includes a diverse set of data management requirements that must become integrated to allow the many hundreds of diverse formats, applications, languages, and user access methods to work together seamlessly. A standard data access format seems feasible by complying with the ISO 15926 standard for product data files that include the engineering information and workflow model (EIWM) to represent data using a master class and attribute library (reference data library RDL) and finally, XML template files to capture the technical descriptions and associated data files, drawings, photographs and other related documentation, Thomson reports that the web based document and content management system, Microsoft Windows Sharepoint Services (WSS) provides a stable and suitable means to establish a global interchange with suppliers, ship owners, building yards and design offices when combined with specialized ship management software applications such as the AVEVA NET Ship Life Cycle Support.

To facilitate data access and translation, adaptive data models are required. The ISO standard 15926 for "*Data integration, sharing, exchange, and hand-over between computer systems*" is primarily used by the oil and gas industry but its principles cover the requirements for data transfer and apply equally well to the ship building industry. Such standards are necessary to facilitate efficient single product model management across enterprises in the global sense. Another similar standard, ISO 10303, "*Automation systems and integration - Product data representation and exchange*," defines the Standard for the Exchange of Product model data STEP. Kassel (2009) reports that, in keeping with the 2008 NAVSEA directive for the development of ship design and analysis tools, the United States navy is committed to the acquisition of intelligent 3-D product model data using the ISO 10303 ship AP protocols (e.g. AP215, AP216, AP218 etc) identified in the NSRP strategic plan. The various APs cover detail data standard requirements that define ship arrangements, ship hull forms, structures, distribution systems including, piping, HVAC, Cable trays, mechanical and electrical systems, equipment subsystems, parts and reference data libraries as well as a miscellaneous category that specifies requirements for finite element analysis, computational fluid dynamics and logistics.

The STEP standard file includes an integrated product structure, graphics, and data with parameterized components that have logical and geometric relationships. STEP standard graphics share a standard product structure and properties that maintain a linkage between product structure and graphics. While STEP reflects the state of the art that is achievable today, most commercial CAD systems still cannot process the STEP APs. Most APs remain under development with different prototypes being developed using different schema. Most importantly, shipbuilders have not embraced ship STEP protocols and have not demanded a ship STEP translation capability from their product model vendors. The NAVSEA migration strategy intends to use the more mature automotive STEP AP214 protocol that deals with Core data for automotive mechanical design processes to populate most of what is required for their ship models.

The NAVSEA "*Leading Edge Architecture for Prototyping Systems*" (LEAPS) is based on an extensible information meta-model designed to provide data to support modeling and simulation tools used by naval designers. The LEAPS product-modeling environment enables importing AutoCAD, Rhino, CATIA and SolidWorks models through the STEP/IGES protocol and provides input files for a variety of engineering analyses without the need to conduct additional pre-processing. The LEAPS product model database is intended to interact with modeling and simulation, various tools and allow full life cycle applications but will remain external to the ship product model (SPM)" (Sullivan, 2011). Efforts to encourage pervasive commonality and culture change to reduce the cost of naval programs argues for the need for a database search and mining tools that will make available to any designer or shipbuilder the full selection of components, but more important, could show designers which fittings, components, or commodity items are most commonly used on other platforms and allow for direct inclusion in the design process. Such a platform requires interlacing the various tools available today, from vendor database, to Internet tools, to 3-D product model integration, and finally the ability to include and translate CAD models from the more common types available to small contractors (AUTOCAD, RHINO, etc.) to load into the high-end product models (CATIA, Ship Constructor, Intergraph, etc.)

Brennan *et al.* (2011) describe a Data Interface Management Engine (DIME) which has been designed by Lloyd's Register (LR) to facilitate transfer of data from ship design offices into the Lloyd's Register Applications. DIME provides a toolkit which facilitates data transfer between ship modeling and analysis applications. The interface toolkit exposes a single Lloyd's Register data format to the outside world that is controlled by the Data Model or Data Schema, which can be extended if required as new functionality becomes available. Data elements have been consolidated across the current suite of applications resulting in a common data model. This allows a single instance of third party data the potential to be passed to numerous LCM and LR applications. DIME also includes a robust geometric kernel and the associated processing for the purpose of creating a geometric representation of the structure suitable for finite element meshing. The ability to create open format finite element models is essential to enable a practical application of ship design analyses.

The Data Interface Management Engine (DIME) is central to the Interface Toolkit. It has been designed exclusively to facilitate the transfer of data to the Lloyd's Register applications. DIME can support ship designers, administration and interface developers. In practice Lloyd's Register staff use DIME throughout Interface creation. When Interfaces are successfully implemented, the DIME performs the role of coordinating data flow, providing a view on the data and progress reporting to Engineers. DIME has a number of possible methods of operation. The desired state is to run in the background, providing relevant progress information as data passes between applications but alerting the user if there is missing/incorrect data. If the user chooses to enter the data in DIME at this time, the data will be stored and the user will not be prompted on subsequent data transfers. The DIME keeps a comprehensive transaction log with timestamp, source application, location, and target application information.

The DIME Interface Toolkit uses XML technologies including, the XML Schema Definitions (XSD's); the eXtensible Stylesheet Language Transformations (XSLT's); and SSX, the Ship Structure eXchange file (LR XML File). The XSLT's transform and filter XML to XML data, prior to transfer to the assessment applications. XSD's are also used in the DIME for filtering and display of data, they define the rules that the data held by an *.ssx file must adhere to. Flexibility is the key to the interface toolkit and DIME uses a modular architecture and the concept of plug-in functionality. The LR Update Manager allows quick and effective means to update components. The Updating of executable files, XSD's, imported driver dynamic link libraries (DLLs) and XLST transformation files is managed within the application and updates are provided as required from the LR website via the "Auto Update" functionality introduced firstly for DIME but now implemented in many other LR Engineering Software applications. The adopted interface approach ensures that LR applications retain their flexibility of information sources and can be used by different teams of people at different stages in the design. The Interface Toolkit has already been used to implement interfaces between LR applications and NAPA, AVEVA Vantage Marine (Tribon), Intergraph SmartMarine3D, AutoCAD (2D Section & Lines plan), IGES (Hull), and HecSalv applications.

A key element for any ship based life cycle data management system would be its model and data format translation tool. Such a tool must enable a seamless ability similar to DIME that will allow file import from supported third party ship design applications. The LR DIME is essentially an expert system that supports both end users and those developing interfaces to the LR applications. As a suitable system for such a purpose the data management system must be able to direct files simultaneously to the appropriate application. In the case of DIME, it simultaneously selects multiple LR applications such as RulesCalc, Ship-Right; SDA; SSC. Such a system must be able to adapt to Dynamic Updates as they are developed and posted on some central node. It must be able to check for updates and install latest drivers and import translators. It must provide a clear view of the imported data format with "traffic light" color coding to indicate correct or missing data as well as help text for all supported data items. It must create some form of an activity transaction log that shows file information, source application, time sent and etc. It must have the ability to import material, profile, and end connection data from designated resource libraries. It must include features to report system information to assist in troubleshooting and associate installed drivers and importer functionality with associated version; store missing data for subsequent data transfers; and customize the tree display and help text to other languages if needed.

Application Programming Interfaces (APIs) are modules that assist the creation of code that will enable developers and ship designers to extract data to the Interface Format file (*.ssx). The same API's are used by Lloyd's Register and 3rd party ship design/CAD suppliers in creating their code. With this approach Lloyd's Register does not have to initiate the implementation of interfaces, since using the API's allow third parties to create the SSX format that DIME can read and that subsequently can be processed in the usual manner by routing directly to any of the supported Lloyd's Register, Martec or Canadian Naval applications.

6.1.3 General Purpose Tools with a Ship-oriented Option

The Dassault Systèmes ENOVIA solutions are a suite of software packages, linked to CATIA, intended to support the design and lifecycle management of a product with communication via web-based portals and PPR (Product, Process and Resource) hubs for the exchange of information between the different members of a project team through their life cycle applications tool (LCA). Specific solutions developed for the shipbuilding industry include AEC hull design, structural design based on standard parametrically controlled parts and software to generate production information for the design. CATIA contains data management tools for use in the build process to track and manage parts. It can also be used to generate a Virtual-Reality (VR) environment of the ship, to assess human factors in the design and operation of the vessel. Their 3-D com tool enables collaborative product development through a common interface and provides access to the various applications and data sources.

IBM offers companies a consulting support capability using their Rational Team Concert to provide a lean collaborative lifecycle management solution. They have developed tools for both engineering design and Product Lifecycle Management, (PLM). For shipbuilding, they have established a strategic partnership with Dassault Systèmes and rely on CATIA for product modeling, DELMIA for their product assembly process detailing and validation and ENOVIA to support the global online collaborative environment for creators, collaborators and even consumers in the product lifecycle.

Team Center Siemens PLM software (2011) includes a variety of specialized tools among those we can find NX-Unigraphics, now version NX-8, the legacy CAD/CAM/CAE software package, but also the Parasolid solid modeler and the I-DEAS CAD software. They offer a range of life-cycle and process management tools. These are sufficiently generic that they can be adapted to a wide range of engineering applications. Examples are as diverse as the Joint Strike Fighter project, Alstom's Industrial Gas Turbines division and LEGO toys. In these cases, the company has provided design and management software to suit the customer's needs.

6.1.4 Ship Dedicated Tools

In combination with Tribon AVEVA offers a ship design software system which includes a Product Information Model, (PIM) that can be accessed by various modular programs to perform standard operations such as calculating hydrodynamic parameters, hydrostatics, hull lines and various structural details. The system defines surfaces, allows structural design, hull outfitting, design re-use as well as development of distribution systems including piping and ship systems in 3-D. Production and assembly data packages can be produced that also include ship construction and welding definitions. The system includes a Data Management module to handle configuration control and also maintain and track revision levels and a large inventory of standard equipment and parts that can be called up into the design.

Another interesting combination has been produced by Sener Marine, the makers of FORAN and in combination with the PTC Windchill product which combines the power and benefits of Windchill with the FORAN Design Environment. The Windchill Gateway for FORAN offers a powerful solution to help shipbuilders address their unique challenges in a distributed design engineering environment. The system allows shipbuilding designers to reliably and easily synchronize their FORAN FBUILDS structures, 3D graphics and attributes with Windchill thereby allowing the sharing of a single, synchronized, graphical view of the ship functional and build structures. The system has been shown to support lifecycle management of FORAN Documents in Windchill including FORAN Data files, FORAN Drawings and FORAN Schematics. A bi-directional exchange of FORAN Product information is possible and improves collaboration by integrating the FORAN design environment with the wider enterprise in terms of business processes and procedures. The data quality is improved by providing all relevant groups with accurate, up-to-date, relevant product content information that's held in a single location. Enterprise efficiency also increases by enforcing standard design processes across multiple design projects and organizations.

The various Shipbuilding Templates allow for additional visualization capabilities and leveraging of Shipbuilding Part Types.

Like CATIA, the vendor of Intelliship provides an API, through which the data required by the LCM tools can be accessed and extracted. The system also uses a "Smart Product Model" of the ship, with rule-based automated systems for estimating the design at the initial stages. Parts are hierarchically linked, so that the effects of design changes will propagate through the model, reducing the delay in reworking of the design.

The open nature of the Nupas-Cadmatic software is intended to facilitate efficient concurrent and distributed design. The software automates many design processes and allows easy sharing of 3D project information between designers, project managers, owners and sub-contractors. The data publishing tool uses smart visualization techniques to quickly create 3D models and facilitate distribution through the internet. The Nupas-Cadmatic software uses a database-centric client server system where the 3D model and documents are all stored in databases and hosted by a database server. In a globally distributed project the data is updated between remote design sites via an online network connection such as the internet or by simply exchanging the file in an email attachment. It is easy to divide design work globally between several design offices with server replication and the addition of new design teams being reduced to a few mouse clicks. Their Internet-based Cadmatic eBrowser is a powerful data publishing tool that enables effective communication between all parties involved in plant investment projects by linking partners through the internet. Plant owners, designers, engineers, subcontractors and customers are all linked to a mutual 3D model allowing easy and concurrent project reviews and plant inspections, facilitated by the ability to virtually walk around the design area.

6.2 Current Practice

6.2.1 Industry-implemented Solutions

Caprace *et al.* (2010) state that available life cycle optimization tools that should enable selecting the correct design options for a given ship and system levels remain poorly applied. Better methods and tools are needed to connect technical design parameters with life cycle performance, and allow technical experts to better assess the impact of design options and parameters on the overall ship performance. An integrated view requires dedicated methods to compare production and operational costs, safety and environmental aspects. It also requires tools for life cycle optimization in the different design and production phases of a ship. The efforts to implement a more collaborative product development in shipbuilding such as the United States naval LPD 17 program have provided improved means within the industry to address such shortcomings, Keane *et al.* (2009). Such enterprise solutions will undoubtedly help reduce corporate amnesia and enable the type of knowledge transfer described by Formentini and Romano (2011) to avoid repeating similar mistakes from project to project.

This need is echoed by Park *et al.* (2007) who developed the DSME Engineering Wizard System that aims to accelerate process performance by managing design execution, promoting collaboration, and maximizing engineering data reusability using a workflow concept. They analyzed Marketing Design in the Korean shipbuilding context, to establish a unique workflow template to identify activities and help organize design experiences into a best practices guide so that tasks could be performed in the most efficient manner. Marketing design is that portion of work that covers the pre-contract award period of engineering performed in a shipyard. A key element required organizing an improved Engineering Data Management (EDM) capability. In most enterprises, the document management system is not harmonized with engineering work. Engineers typically search for data to perform individual specific tasks and are responsible for storing and managing data in addition to and apart from their primary engineering responsibility. Hence, effective document access, process definition, system maintenance, and process monitoring are essential solutions to improve industrial capability and can be implemented in a practical manner.

Specific application of the project life cycle model (PLM) is reported by Le Duigou *et al.* (2009). Their study audited several companies to better understand how digital and collaborative engineering was performed and to determine best practices using a benchmarking system to rate software tool capability and efficiency. They found that product improvements developed by designers due to user feedback, improved methods, and optimization or testing were not reproduced on other company products unless the particular designer was specifically involved in their production. They noted that the methods used for producing the Bill of Material (BOM) technical data definition was performed manually and was only updated when there was a major modification of the product design. They also noted inefficiencies in the retrieval of legacy product design information as well as references and specification and noted problems in the methodology for estimating raw material requirements. By developing an expert system that would construct a CAD file to describe the object based on its defined functional requirements and other constraining criteria, much like a mathematical spreadsheet, it was possible to automate the creation of the BOM, maintain it simply whenever a functional requirement was modified and enable storing it within the PLM database. It is possible to automate the various analysis required for the product from the BOM data file. The development of a standard methodology for common shipbuilding components is underway and expected to rapidly progress to enable more efficient product design development.

Nishiyama *et al.* (2010) introduce their approach of design quality improvements at initial and detail design stages, and applications of 3D design information at production stages by using the 3D-CAD MATES (Mitsubishi Advanced Total Engineering System for ships) developed on 1980's and functionally improved on regular basis.

Wu and Shaw (2011) propose a basic ship design knowledge model for information storage and retrieval using a knowledge-based engineering system. They analyze the design flow advantage of applying a document based KBE system. In current practice, ship design relies on using past experience and with reference to document based ship data information. The method presumes that the reference ships are actually optimal design solutions and that deviations from their designs are to be avoided. They propose that, by adopting a rule-based reasoning approach, an improved development of conceptual ship designs will be possible. They describe their information technique architecture as containing knowledge based engineering (KBE) that is coupled to design rules and an inference engine to provide an integrated framework for ship design knowledge. Their document management system allows development of specific vocabularies and exact meanings using standard xml format documents. In parallel, another system is developed to list the owners' functional requirements. Using standard methods, an initial design requirements document is formulated by applying the owners' requirements to the KBE database. As the design development continues, principle dimensions of the hull, the ships power, propeller design and other details are developed through a basic design graphical user interface following a logical sequence. They show that as design rules, performance requirements or other details arise, it is possible to rapidly and simply update the data model for immediate changes to all the related design details and analysis results. Such expert systems are thought to become more and more common in the industry to address various ship types. With time it is expected that standard libraries will be created to standardize the ship design and build process.

Li *et al.* (2011) discuss the merits of translation as compared to using a common standard to enable ready interchange of product models created using different modeling and analysis systems and report on a comparison made against Tribon and AVEVA PDMS. While it is expected that there should exist a single repository for information and as enterprises grow into a global network, and new software systems emerge, it is still necessary to exchange data among heterogeneous CAD systems and to migrate legacy data to next-generation CAD systems. Clearly, incompatible file formats prevent simple migration and it is not only time consuming to translate files but it is difficult to maintain sufficient translating capability as more efficient file formats are created by the industry and further complicated by operating system utility standards design. The authors report success with a method that creates repositories based on ISO 10303 AP277, the process plant configuration and ISO 15926, integration of life cycle data for process plants including oil and gas production facilities. They developed a ShapeDB, which is constructed to manage the geometry information of the product data model that refers to the equipment catalogue defined by ISO 15926. By designing the ShapeDB Schema in such a way, that Tribon is able to populate the necessary database as a neutral format conforming to AP227 and ISO15926, the PDMS is able to directly import the information by accessing the standard neutral format as well. This example reflects to a degree the difficulty that is prevalent thorough out the industry today and shows the difficulty of applying enterprise wide solutions.

Shao *et al.* (2009) report on progress made with design of ships machinery using an expert system for the computer aided conceptual design of ships engine room automation (ESACD). Their solution custom designed an application using an existing Ship Data Warehouse system, a configuration selection assistant (CSA), and the design scheme decision assistant (DSDA). Their process integrated the Fuzzy c-means algorithm (FCM) with Rough Sets Theory (RST) to assemble configuration rules from the existing database. Given the fundamental importance for the conceptual design of a ship's engine room, and its impact on the ship cost and performance, a design method based on more than designers experience is well justified. Their case study demonstrated the validity and utility of the expert system in the design of an engine room for a 50,000 DWT bulk carrier and effectively demonstrated. With improved knowledge of computer aided design methods, that such expert systems show great promise for improving the capability of future shipbuilding design toolsets

Whitfield *et al.* (2011) report on an approach for managing the exchange of engineering product data between geographically distributed engineers, designers, and analysts using a heterogeneous tool set for the through-life design of a ship. Their method followed the methodology outlined by the pan-European maritime project, VRShips-ROPAX 2000 that showed how information technology could be integrated into the design process. The methodology, file structures, and management systems are more generic however seem similar to those described for the LR DIME. The use of neutral ship product data based on STEP protocol and a common model within an integrated design environment (IDE) was maintained. Their demonstration started with an empty common model which was initially populated with a hull-form, decks and bulkheads uploaded by an engineer in France. The various users configured their design and simulation tools by linking them with tasks within the various process models and building a consistency map to be managed by the system consistency manager. In turn, the common model was populated by users spread across Europe using a closely-coupled approach. XML was chosen as the appropriate technology for the storage and communication of ship product data primarily due to its familiarity within the IT support community. The VRShips IDE approach was found to ensure that the correct data in the right form and at the right time was provided for the users and that the resultant design activity was timely and appropriate. The authors caution that as suggested by Gielingh (2008) that it is virtually impossible to create a single integrated information model that meets all industrial criteria, but rather that it is necessary to create a more pragmatic, bottom-up approach for and build in some dynamic capability to adjust for different ship types.

Maopoulos and Ceglarek (2010) report about practices for design verification and validation in product lifecycle. Their review of required processes show that virtual prototyping within the PLM construct enables design verification of dimensional and many other properties of product more effectively compared to conventional physical models and suggest that future trends will tend to rely less on prototyping and physical rather than digital model studies. In particular, performing assessments earlier in the product lifecycle helps industry reduce project risk and facilitates optimization of design options well ahead of design freeze deadlines.

Papanikolaou (2009) provides an introduction to a holistic approach to ship design optimization and defines the generic ship design optimization problem which can be solved using advanced optimization techniques that enable computer aided generation and selection of optimal designs. They describe typical ship design optimization problems with multiple objectives that can lead to improved cargo capacity, reduced powering or better safety or survivability. During the initial design phase of conceptual or preliminary design, conflicting requirements can be resolved, as can many other variables such as cost, weight, and speed. The PLM database will facilitate design optimization, particularly if it is close coupled to enable selection of alternate components and space reallocations. The more investment that is made to develop analysis methods to study the influence of design variables on the project, the greater will be the potential cost and schedule savings.

Olmos (2011) describes the data management method used by NAVANTIA S.A., Cartagena, since 2004 for the S80 Spanish submarine project. Their method is based in the PTC WindChill PLM system, which is linked to the FORAN design tool by means of the FORAN PLM tool set (FPLM) developed by Sener marine. The submarine was first defined in FORAN and separated into various "zones" and "systems". These were then translated into WindChill by a specific "Strategy of Construction" which allows WindChill to show every item in a constructive, functional or geographic breakdown. The database method allows access to more than 250,000 objects with complete drawings, specifications and 3D virtual reality modeling for distributed systems, structures, machinery and bills of material. The method presented in the paper covers the whole design and construction phases until the delivery of the ship to the owner. After delivery, NAVANTIA provides the owner with all the information needed to populate their own PLCM throughout their operation and maintenance phases. De Góngora (2009) provides more detail about the expert system module developed within the FORAN shipbuilding tool set that allows ship designers to design a complete HVAC distribution system using functional requirement criteria. The code automatically calculates duct sizing, routing layout, and bills of material down to the level of hangers and clearance dimensions, as well as a complete flow and pressure loss calculation report. Olmos and Valderrama (2011) report on the electrical cable system design methodology used for the design of the S90 submarine based on a relational database and automated system design capability. Automation was considered essential, given the large number of components and the need for precise routing and installation. In particular, they note that by programming a particular component correctly once, and including its connectivity, seating, and so on, it is possible to locate many of these items throughout a design by simply calling them up and pasting wherever required.

In addition to the efforts taken by shipyard engineering and code developers, some note should be made of Classification Society software solutions being developed for their customer base. The LR approach with their DIME system supplied as part of their Rules Interface Toolkit initiative is to allow ship designers ready access to Rule and procedural checking alongside their preferred design tools. Their RulesCalc software tool enables ship designers to quickly assess designs against the Lloyd's Register's Rules and Regulations for the Classification of Ships, the IACS Common Structural Rules for Double Hull Oil Tankers and the IACS Common Structural Rules for Bulk Carriers. The DNV approach with their Yard Package provides a more complete Enterprise solution. In addition to supporting model transfer and rules assessment support, the DNV Nauticus Early design and Brix Foundation package together with their legacy Nauticus Hull and Nauticus Machinery packages, the Environmental Performance System (EPS) and TenderSuite provide a near implementation of a product lifecycle capability. The Brix Project Manager provides a powerful mechanism for knowledge management and allows setting a common project space for all ship design project members. By implementing information workflow as an important technology, DNV Software helps existing and new customers find the right balance between emerging technologies and new ways of engineering and includes a full design and analysis capability in their suite to help comply with classification criteria.

6.2.2 LCDM Facts Book: How it works on a Day-to-day Basis

In addition to ship specific LCDM products, purpose built applications can be developed by service providers like IBM Global Business Services who provide consultation, integration and implementation services around the mySAP Product Lifecycle Management solutions. Typical implementations enable enterprise solutions access to developing and legacy information across their entire business chain to promote faster and more accurate decision-making. Collaboration capability for design management and product maintenance helps reduce design and production time. Product development capability is enhanced and time-to-market is reduced with additional benefits provided by improved market visibility and distribution. Improved production is facilitated by gaining control over planning, purchasing, operation, maintenance, upgrades, and replacements. Product quality improvements are made possible by integrating quality management across development, production, and maintenance. While the day-to-day processes that utilize the capability made possible by an implemented PLM and LCDM to an enterprise will vary, however, depending on the requirement, specific processes and methods will not vary. The methods for data access, retrieval, network sharing, model maintenance and process development will remain similar across many enterprises.

A typical mySAP Business Suite implementation of Product Lifecycle Management would include a scale able technology platform to integrate existing enterprise technologies and enable establishing a new generation of cross enterprise processes. Components would include an enterprise resource planning module, a supplier relationship management component, an enterprise access module to manage enterprise data and provide content designed to address user roles, some means for allowing cross enterprise distribution and capture of information, and a means to maintain a knowledge bank for reference, training, and documentation.

In the modern economy, with scaled down operations and the need for competitive advantage, the requirement for a well-integrated application of knowledge and experience to win building contracts is more important than ever. The need to shorten the design cycle and improve its accuracy, particularly in the pre-contract stage, to better mesh with tendering constraints and avoid costly re-design requirements, will more than ever require ship yards to focus on more efficient and faster design analysis. While the basic shipbuilding process does not vary much between yards, customized coordination of design and procurement and the delivery of essential lifecycle data documentation remains a key constraint when, for example a typical cruise ship build is considered, that requires involvement of many hundreds of groups that include national authorities, regulators, consultants, turnkey suppliers, various engineering offices and subcontractors.

To staff such a volume of documentation for such a large group of stakeholders on schedule and without technical error or product design impact requires a significant and well thought out data management capability. Such a capability must rely on efficient automated data processing systems. According to Watt-Pringle (2011), large shipbuilding firms, including Hyundai Heavy Industries (HH) and STX-Finland Cruise Oy, are investing in various modern computer aided data management methods to streamline their shipbuilding process during the planning and design stages to maintain total control of the schedule and have the ability to respond to rapid changes in information that reduce risk at each stage of the process particularly in consideration that the principles of shipbuilding are based on concurrent design, engineering and installation.

6.2.3 Data out from the Survey

The survey statistics, albeit drawn from a small sample size of 23, confirm observations made by Caprace *et al.* (2010), that while the shipbuilding industry is allowing some free data access and using the advanced architecture of STEP or XML file systems only in certain cases, most practices prefer to use format data structures that are native to their legacy application tools and continue to operate closed and restricted data access systems. The respondents reported using various versions of the ship dedicated tools described in section 6.1.3, however there was little to no mention made concerning the use of open format enterprise wide LCDM or SPM methodologies or any mention given to any of the industry-implemented solutions that were discussed by section 6.2.1. Given that some progress was reported in the use of advanced design and analysis tools by the survey compared to ten years ago, and that certain major shipyards, who may not have participated in the survey are now to use LCDM and SPM, it is expected that, especially as economic pressures continue, companies will adopt the improved efficiencies afforded by a more widespread use of enterprise solutions for knowledge management using SPM and open architecture methods. Please refer to chapter 8 for more details on the survey.

7 OBSTACLES, CHALLENGES AND FUTURE DEVELOPMENTS

7.1 The Impact of Regulations on Various Stages of the Ship Life

Faced with increased shipping activity and consequent potential increase in ocean disasters as well as the related impact on the environment and human health issues related to the management of the overall ship lifecycle, regulation authorities decided to publish new rules. Some rules have already been applied while the remainder will be invoked in the very near future. The following three documents provide examples of such new regulations:

- "Technical Guidelines for the Environmentally Sound Management of the Full and Partial Dismantling of Ships", the so-called Basel Convention, issued in 2002 by a UN Technical Working Group (http://www.basel.int)
- "Safety and Health in Ship Breaking: Guidelines for Asian Countries and Turkey" issued en 2004 by the International Labour Organisation (ILO) (http://www.ilo.org)
- "Guideline on Ship Recycling, Resolution A.962(23)" issued en 2004 by the International Maritime Organisation (IMO). Guidance of "best practice" for
  - flag, port, and recycling States
  - shipowners
  - shipbuilders
  - marine equipment suppliers
  - recycling facilities

  (http://www.imo.org)

A rather simple comparison of the scope covered by these regulations is presented in Figure 4 below.

Some efforts are made to ensure a better coverage of the various items by the regulations. More details may be found on the IMO web site.

7.2 Survey Analysis and Product Lifecycle Management

For more details on the survey, please refer to chapter 8. While limited by the number of participants and the geographical location of the participants, the PLM survey results do reveal some challenges in the application of product lifecycle management in the marine industry. Firm statistical conclusions cannot be drawn from the limited samples set, so this section will focus on several themes that appear in both the survey results as well as the literature reviewed by this committee.

The survey revealed that during the design stage a wide range of engineering tools are required. Other than AutoCAD, in-house spreadsheets and custom applications were the most frequently cited tools used. This may reflect both the focus of the European marine industries on specialized, one-off ships which require specialized

	IMO	ILO	BC
Role of stakeholders and other bodies	×	×	×
Design and construction of ships	×	×	
Operation and maintenance of ships	×	×	
Preparation for ship recycling	×	×	×
Occupational safety and health in ship scrapping operations	×	×	×
Environmentally sound management at ship scrapping facilities	×	×	×
Design, construction and operation of ship scrapping facilities	×	×	×

Figure 4: Comparison of the respective scopes of IMO, ILO and BC regulations

engineering skills not supported by standardized tools, and the current fragmentation of the design process under "Design for X". "Design for X" may further fragment the types of engineering data and tools required for successful design depending if the yard and owner are primarily interested in cost, safety, environmental performance or etc. For such custom spreadsheets and tools, the end user is also the tool developer. Therefore, the end user would be required to maintain compatibility with neutral-format standards such as XML and STEP using their own investment of time and money. A further difficulty raised by Gischner (2006) is that the lifecycle of marine products may be up to 50 years, but the typical IT system lifecycle is only 10 years. This implies that many IT advances will occur over the vessel's lifetime and therefore the PLM data must be repeatedly moved to new systems via new investments.

While not confirmed by the limited data in the survey, the survey results would seem to suggest that the customer demand for data in these formats is not strong enough to encourage this investment. Further support for this assertion can also be found in the data transfer section of the survey, where scanned and native format transmissions of data were the most and second most popular means of moving data and little evidence of STEP or XML formats was found. Furthermore, most data transfers appeared to be between shipyards and subcontractors for either design or construction, with little data transfer to owners or other through-life actors. Moredo *et al.* (2009) have a slightly different take on the origin of this problem, noting many yards are not set up to make profit from after-delivery servicing and support, and that if more were, this might spur development of more complete data transfer and associated PLM solutions.

Notable as well is the wide adoption of general-purpose engineering tools for which the marine market is likely a minor component - indicating that marine-specific neutral-format export capabilities may not be a priority of the developer. AutoCAD, Excel, and Rhino all fit in this category, and during preliminary design were the first, third, and fourth most commonly cited tool respectively. Many of the classification societies have been pushing lifecycle support through extensions to their own custom toolsets (Safehull, BV Mars 2000, etc.) of which six were included in the survey. However, at this time, the survey revealed that the use of all six of these tools peaks during basic design, presumably for plan approval, and then falls off again. This pattern suggests that such tools are not capturing all aspects of the design necessary for complete PLM, although they may be more successful in supporting lifecycle class activities such as surveys.

While the survey does not reveal the exact reasons for the lack of neutral-format PLM solutions at the moment, recent literature has suggested some practical problems. Boesche (2010) noted that neutral-format files for machinery and outfitting components typically had the shortcomings of:

- Very large file size;
- Models were often too detailed for overall design integration purposes;
- Contours and surfaces may get tessellated during conversion with loss of quality;
- Important metadata and attributes are often lost.

Boesche presented an alternative, centralized parametric modeling capability that could directly produce native file format renderings for a variety of systems as an alternative. Authors and software vendors also push for a single, centralized repository solution. Recent progress in the U.S. Navy acquisition community has shown progress in using STEP, S1000D and neutral-format files as the basis of a PLM system for high-valued, specialized naval combatants, Briggs *et al.* (2009). In such cases, there is only one customer for the lifecycle of the vessel, and a small number of shipyards and vendors compared to the wider commercial shipbuilding world. However this experience suggests that the challenges associated with neutral-format data exchange can be overcome with a strong enough customer demand.

The ideal format of the PLM data structure is still being debated in the literature. As mentioned, Briggs *et al.* (2009) advocated a standard based on STEP and S1000D. Sharma and Kim (2010) advocated a modular structure to a PLM using both geographical and functional zoning, and suggesting neutral-format for data exchange. Donoghue and Cartwright (2009) provide an overview of a modular commercial system focused on product data as well as design requirements documentation and other process-related IP. Thomson (2010) presents a different commercial system based on ISO 15926 data modeling to associate components, data, and calculations, as well as universally unique identifiers (UUID) assigned physical design components to provide better granularity for change revision control.

Thus, at this time the survey and literature review suggests that the marine industry has not yet routinely applied robust PLM solutions for design and operation of vessels. Some standards, such as S1000D, via SHIPDEX, appear to be gaining widespread acceptance. This uptake may pave the way for future PLM advances. At the present time, identified key limitations for marine PLM are:

- The state of the art in the industry appears to be native file format transfers or scanned documents, and outside of shipyard and subcontractor ties, little data appears transferred.
- The product lifecycle (20–50 years) outlives the current IT system lifecycle.
- Customer demand and opportunities for shipyards to turn lifecycle support into revenue appear to be lacking.
- Continued research into the description of the ideal structure for marine PLM tools is still on-going, with both neutral-format and proprietary solutions still being proposed and debated in the literature.

7.3 Design Process and Optimization

As reviewed in Section 4, a key challenge with ship design and optimization remains the automated creation of 3-D FEA models and structural descriptions such that advanced optimization tools can be applied in at least a semi-automatic fashion. Many integrated software packages feature such tools, however, the use of such packages often preclude the use of custom or in-house optimizers to then drive the problem. Additionally, should a design based upon ultimate limit states be required, the non-linear FEA models require additional information about residual stresses and initial imperfections in the structure, Benson (2009). This information is not typically stored or processed in the existing system. Given the complexity of such failure modes, the general desire to be able to address multi-objective optimization, and to include some measures of uncertainty such as reliability-based design optimization (RBDO), the use of metamodels and parallel processing is a growing area of interest. Kriging models and other surrogate modeling techniques have been explored in limited depth at the present time but clear recommendations on their use cannot yet be made, and more research on these topics is required, Purswani *et al.* (2010).

For a large passenger ship optimization, Caprace *et al.* (2011) were able to develop multi-objective Pareto frontiers successfully, but noted that the following research needs were still required:

- Fast and reliable models for structural constraints such as fatigue and loads.
- An open interface/plug-and-play system for structural analysis modules is highly encouraged.
- Further integration of the structural optimization tools with the major CAD/CAM and FEA systems to allow faster and more automated optimization.
- Further use of multi-stakeholder, multi-objective solutions for more reliable industrial solutions from the process.
- Better integration of maintenance and lifecycle costing into the initial stages of design.

A further challenge for ship structural design remains the difficulty of changing or upgrading ship structure once constructed. In light of changing environmental regulations, the general ship design community is exploring what is necessary to include such uncertainty in the design process. However, many of these models rely on being able to design for upgradability or to switch out components later in the vessel's life, something which is difficult for structures, Niese and Singer (2011). Commenting on a design-stage model attempting to include maintenance and repair costs in the initial structural design decisions, Turan *et al.* (2009) noted that the current state-of-the-art had several shortcomings. The following challenges and future research areas were noted:

- Inability to obtain accurate repair cost and maintenance strategy data from ship-owners for design hampers what can be achieved today.
- Systems for advanced reasoning with vague and imprecise verbal knowledge of repair costs would be beneficial, as well as more study of advanced data regression techniques.
- More advanced lifecycle design models that include the repair approach of the owner would be beneficial.
- Ability to include uncertainty in the economic side of the picture (e.g. freight rates) would also make such models more useful.

The literature reviewed by this committee suggests that the research and industrial communities are actively seeking more advance structural design methods that can reliably trade between conflicting objectives of cost and through-life performance. Practical multi-objective frameworks including higher-fidelity structural models and through-life maintenance costs remain challenging. Such procedures are an active area of research and development with improvements being sought for both optimization frameworks as well as prediction modules to compute objective function values.

8 SURVEY ON IT TOOLS AND DATA EXCHANGE

To base the "state of the art" sub-chapters of the report on actual data, the Committee decided to distribute a web-based survey among shipbuilding stakeholders. The target bodies of the survey were shipyards, design offices, research centers, software vendors and universities. Each Committee member was in charge of contacting people in a specific geographic area. Despite an easy access and a few questions the Committee got answers from only 23 bodies. It is insufficient to draw statistics but it is representative enough to analyze and show trends.

8.1 Overview of the Results

Number of answers: 23

Company profiles: Almost half of the companies (11) are shipyards. There were 4 design offices, 1 class society, various suppliers and no ship owner.

Company fields: Almost half of the companies (12) were acting in the capacity of merchant shipbuilding. Two companies were acting only in naval construction and 8 companies were acting in offshore but none exclusively for offshore as they were coupled with certain shipbuilding activity.

Company locations: Survey responses were obtained from three continents. The majority of responses came from Europe (15). Asian companies provided 6 answers while North American firms provided 2 answers.

Company sizes: Using an average value of less than 500 employees to define an SME, the responses were distributed at about half from SMEs and half from large companies and groups. One response came from a micro enterprise (1 to 5 employees) and 6 responses came from the largest category that was defined (e.g. more than 3000 employees).

Occupation of the contract in charge of filling in the survey:

Office Manager & Supervisor:	6
Computer & Information Systems Manager:	2
Research & Development Manager:	6
Design & Conception Manager:	7
Production & Manufacturing Manager:	1
Other:	1

Confidentiality issue: 6 persons chose not to complete the entire form due to confidentiality issues related to certain of the questions.

8.2 Utilization of IT tools

8.2.1 CAD Tools

The shipbuilding industry is included in the overall modern design and production process that involves many companies and needs standards. Therefore, it is not a surprise to find Autocad definitely at the first rank for CAD systems. Almost 75 % of the companies are using it whatever the size of the company is. Furthermore, Autocad is used all across the deign loop from preliminary design through basic design and up to detailed design.

8.2.2 Class Society Tools

Among the shipyards which answered the survey, ABS Safehull is mainly used in Asia while BV Mars 2000 and GL Poseidon are the favorite tools in Europe. As expected, these tools (whatever brand) are mainly used in the basic design stage where the sales price must be decided.

8.2.3 General Purpose Structural Analysis Tools

Three software tools were proposed in the survey: ABAQUS, ANSYS and NASTRAN. No other tool has been proposed by the answering companies. They are all used on an equivalent basis with a few more hits for NASTRAN in the basic design stage. With respect to equivalent surveys (ISSC 2003, WONDERMAR European project) carried out almost 10 years ago, it is noticeable that such tools are used all along the design loop and not only during the detailed design stage as it was previously. This means that the shipbuilders are facing more challenging projects (both from the technical and the economical point of view) and perhaps tuning is needed from the early beginning of the project even in a series of sister ships.

8.2.4 Computational Fluid Dynamics

Four tools were proposed in the survey (Diodore, Fluent, Shipflow, ANSYS CFX). Fluent is clearly the best known product. These tools are still used in larger organizations but less often in smaller bodies and less used than structural analysis tools. The explanation for that is related to the more difficult access to these tools particularly given the necessary skills (required academic level for their appropriate application), the license pricing and the required resources for CFD analyses (computation and modeling times, computer power . . .). As expected, the stamping ground for CFD is primarily used during the preliminary design when critical choices involving hydrodynamics are made to define the main characteristics of the ship (hull shape, propulsion and other potential design drivers . . .).

8.2.5 Other Tools and non Listed Solutions

Almost half of the responders admitted using spreadsheets somewhere in their design loop. But the majority used in-house developed custom tools. These results clearly demonstrate a need for customization. Once more, innovation is an explanation but the complexity of the ship herself remains an issue difficult to be addressed by the software providers. At least a full integration is not possible in most cases, but various special tools are often needed to address the complete design process and in-house developments or macros are still required. It is interesting to note that the number of in-house tools decreases with the advancement of the design loop: the more finalized the project is the more integrated the solutions become. Nevertheless this trend remains marginal (In-house developments: PD: 13, BD: 12 and DD: 11). Several in-house developments are based on the open software community.

8.3 Data Exchange

8.3.1 Data Access

The current trend is to restrict access to the data. Among the partners of a shipyard the need to exchange data with subcontractors for manufacturing, suppliers, or other building yards, repair yards, or owners, the usual data exchange status is No "access" in most cases. Two particular cases have to be considered: Subcontractors for design have often a full access to the data (sharing CAD data bases, e-procurement . . .) and Class societies have often a "read-only" access for the approval of the drawings. The crew is usually not given an access to design data (outstanding examples exist in the Navy).

8.3.2 Data Exchange Media

The favorite media used in the day to day exchange is definitely e-mail. More integrated electronic means such as direct FTP, VPNs or direct connection to a database are seldom used. These integrated solutions are mainly used to improve the efficiency in the design stages (still sharing CAD data bases and e-procurement).

8.3.3 Data Format

The primary formats used are restricted to the "native tool format" and the "scanned document" format while advanced formats such as STEP or XML remain seldom. This situation implies specifications for PLM tools from both storage and retrieving point of view.

8.3.4 Ranking of Data Exchange

The panel was asked to provide the survey with a ranking (from 1 - worst to 5 - better) of the present data exchange they are using within their company. As is usual for such cases, the answers almost fit a normal distribution with mean value 2.98 and standard deviation 0.25. But when the survey is restricted to subcontractors, suppliers and class societies, the average rank is increases to 3.16 while the standard deviation reduces to 0.11. This last result clearly shows that in the day to day work, data integration is actual but not yet extended to many of the stakeholders that play a key role during the life cycle of the ship.

8.4 Overall Survey Conclusion

While the survey size of only 23 respondents is not sufficient to draw reliable statistics, and while the answers are not adequately spread throughout the world, some of the results help support expected conclusions. A real effort is required to better integrate data from the initial design to the final disposal stage. It is not obvious how to address such an issue but some advances have clearly emerged during the last decade.

9 CONCLUSION

The approach to ship design has become more systematic, more rational, more analytical, and more transparent in its justifications. The quality of the product ship and its safety and reliability have benefitted from this new approach that requires a concerted application of human creativity in problem formulation and application of methods for systems analysis and optimization, using the increasing abundance of computer-based technologies. These developments have been to the advantage of the marine industry and of its customers. Effective solutions in shipping provide the foundation for global trade and global standards of living. Automated monitoring systems are commonly fitted to many types of ships. A brief look into the future has shown that much work still lies ahead. The same methodologies are suitable to guide us further. The international community in ship design should be encouraged by its past achievements and should confidently face the new challenges ahead, Nowacki (2009).

The use of computer tools and electronic devices is now a reality within the overall ship lifecycle. From design to disposal through operation pertinent data are generated and stored. The larger data sets are produced during the design stage. Parts of these data sets are often open to external bodies (sub-contractors, class societies). The real challenge shipbuilding and shipping industries are facing now is to integrate all the available information and make it accessible during the whole lifecycle of the ship. In recent years, the need for cost effectiveness has led to:

- The anticipation of technical stops to minimize the loss of income using a rational preventive maintenance based on an up-to-date database (steel structures, outfitting ...)
- A maximized value on the second hand market of a ship able to display its effective state
- A better brand image for the ship owner able to demonstrate a well driven management of the fleet from the safety side (safety of passengers and/or cargo, minimized risks of pollution ...)
- A minimized impact on the environment for the whole life cycle: environment friendly building procedures, impact of maintenance activities, encouraging recycling instead of garbage collection during ship disposal, integrated ship design and management to minimize energy/fuel consumption ...

This observation is not a single point of view, but presents a real trend that has already some effective examples in practice: GL Pegasus system and the last releases of BV

Veristar Hull include the results from the European Project CAS (2008) to offer a database-oriented support for hull monitoring data.

The regulations will have, as usual, a noticeable impact on the behavior of both ship yards (building, repair and decommissioning yards) and ship operators.

Finally, the maturity of the software tools and the power and reliability of the hardware tools may facilitate the emergence of a more integrated solution that can handle a comprehensive set of data for the entire lifecycle of the ship in the short term.

10 ABBREVIATIONS

ABS	American Bureau of Shipping
ALC	Analytical target cascading with Lagrangian Coordination
AM	Analysis Module
API	Application Programming Interfaces
ATC	Analytical Target Cascading
BD	Basic Design
BLISS	Bi-level Integrated Systems Synthesis
BOM	Bill Of Material
BV	Bureau Veritas
CAD/CAM/CAE	Computer Aided Design/Manufacturing/Engineering
CALS	Continuous Acquisition and Life-cycle Support
CAPEX	Capital expenditures
CAS	Condition Assessment Scheme for ship hull monitoring
CFD	Computational Fluid Dynamics
CIM	Computer Integrated Manufacturing
CO	Collaborative Optimization
CSA	Configuration Selection Assistant
CSR	Common Structural Rules
CSSO	Concurrent Sub Space Optimization
DACE	Design and Analysis of Computer Experiments
DD	Detailed Design
DDG	Guided missile destroyer (US Navy)
DFA	Design For Assembly
DFC/DTC	Design For Cost, Design To Cost
DFE	Design For Environment
DFM	Design For Maintenance
DFP	Design For Production
DFR	Design For Robustness
DFRR	Design For Retrofitting & Refurbishment
DFS	Design For Safety
DFX	Design For X (where X stands for Production, Maintenance ...)
DIME	Data Interface Management Engine
DLL	Dynamic Link Libraries
DNV	Det Norske Veritas
DOE	Design Of Experiments
DOF	Degree Of Freedom
DSDA	Design Scheme Decision Assistant
DSP	Decision Support Package
DWT	Dead Weight Tons
EDM	Engineering Data Management
EEDI	Energy Efficiency Design Index
EIWM	Engineering Information and Workflow Model
ERP	Enterprise Resource Planning

EU FP(6 or 7)	European R&D Frame Program (6=previous, 7=on going)
FCM	Fuzzy C-means Algorithm
FEA	Finite Elements Analysis
FSA	Formal Safety Assessment
GBS	Goal-Based Standards
GL	Germanischer Lloyd
GUI	Graphical User Interface
HVAC	Heating, Ventilation and Air-Conditioning
IACS	International Association of Classification Societies
ICAM	Integrated Computer-Aided Manufacturing language
ICT	Information and Communication Technologies
IDE	Integrated Data Environment
IDEF	Integrated DEFinition
IDM	Integrated Data Management
IGES	Initial Graphics Exchange Specification (geometric data file format)
IHM	Inventory of Hazardous Material
ILCM	Integrated Life Cycle Management
ILO	International Labor Organization
IMDC	International Marine Design Conference
IMO	International Maritime Organisation
IPD	Inexact Penalty Decomposition
IPDE	Integrated Product Data Exchange
IPPD	Integrated Product and Process Development
IPR	Intellectual Property Right
ISO	International Standards Organization
ISSMM	Improved Ship Structures Maintenance Management
IT	Information Technology
KBE	Knowledge-Based Engineering
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCP	Life Cycle Profit
LCP	Life Cycle Performance
LMLO	Linearized multi-level optimization
LPD	Amphibious Transport Dock (US Navy)
MADM	Multi Attribute Decision Making
MARPOL	International convention on MARitime POLution
MCDM	Multi Criteria Decision Making
MCO	Multiple Criteria Optimization
MODM	Multi Objective Decision Making
MPM	Manufacturing Process Management
MS WSS	Microsoft Windows Sharepoint Services
MSC	Maritime Safety Committee (IMO Committee issuing guidelines)
NURBS	Non-Uniform Rational Basis Spline
OLD	Optimization by Linear Decomposition
OPEX	Operational expenditures
PD	Preliminary Design
PDM	Product Data Management
PIM	Product Information Model
PKI	Public Key Infrastructure
PLM	Product Life Cycle Management
PPR	Product, Process and Resource
QSD	Quazi Separable Decomposition
RBF	Radial Basis Functions

RDL	Reference Data Library
REL/ROB	Reliability/Robustness
RFR	Required Freight Rate
RMS	Root Mean Square
ROPAX	Roll On Roll Off also carrying passengers (PAX)
RS	Response Surfaces
RST	Rough Sets Theory
SCF	Ship Construction Files
SID	Structural Inspection Database
SM	Synthesis Module
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	Safety Of Life At Sea
SPM	Ship Product Models
SQL	Structured Query Language (database handling language)
SSX	Ship Structure eXchange file (Lloyd's Register XML File)
STEP	Standard for the Exchange of Product model data
TDP	Technical Data Package
UCL	University College London
UML	Unified Modeling Language
UN	United Nations
VR	Virtual Reality
WAN	Wide Area Network
XML	eXtended Markup Language

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