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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

Design Methodology, Product Lifecycle Model, Optimization, Classification Society, Lifecycle Structural Management, CAD, Design Software.

CONTENTS

1. INTRODUCTION

Structural design methods continued to increase in both scope and fidelity over the time period covered by the 19th ISSC. The committee's work revealed progress along themes established by previous ISSC IV.2 Committees. Advances addressing lifecycle modeling, lifecycle data management, risk-based design, and optimization continue to appear in both design methodology and design tools. In the 19th ISSC, the Committee elected to revisit a survey of classification society software packages first conducted during the 14th ISSC in the year 2000. Classification societies continue to play a central role in the development and maintenance of ship structures from design inception through disposal. Thus, their software offerings are frequently deeply involved in the design and operational support of ship structures. In the intervening 15 years since the first survey of these tools, finite element analysis (FEA), spectral fatigue assessment, and lifecycle data management have all grown significantly in prominence. Not surprisingly, these capabilities are now woven into the software packages of most classification societies. Chapter Five of this report provides an overview and comparison of ten societies' offerings.

The preceding IV.2 Committee chose to organize their report around the concept of lifecycle management (LCM), with a strong focus on data management. The current Committee continued this investigation with an update on developments in this area in Chapter Six and with additional, relevant discussions about design tools in Chapter Three and a classification society review in Chapter Five. The current committee also chose to expand the focus beyond data management to include design approaches for lifecycle performance, structural monitoring approaches, and integration with repair. These are all topics where the committee saw exciting, but generally preliminary, initial studies. The Committee foresees rapid future growth in these topics.

Probabilistic modeling, risk-based design, and the inclusion of uncertainties in design continue to receive attention as well. Sustained efforts to include more realistic safety scenarios and sources of risk in early-stage and detailed structural design are apparent throughout the literature. Such modeling now routinely goes beyond safety and risk topics, with scenario-based design and epoch-era analysis techniques also continue to be explored by the community. Chapter Two presents a comprehensive review of recent advances and literature in these areas.

Design methods are undoubtedly influenced by the available design tools. Perhaps no tool is more discussed than optimization. The Committee's review reveals that larger and larger optimization problems are becoming computationally practical. Building off the overall optimization strategy first presented in the last ISSC, the Committee continued its discussion of the role of optimization in design and the types of advances in optimizers, computational hardware, surrogate modeling, and links to lifecycle cost optimization and production optimization in Chapter Four. Design tools, including links to lifecycle costing and analysis, are reviewed in Chapter Three.

While the Committee's report primarily focuses on the impressive progress made during the last three years, important gaps still remain. These have been identified throughout the Committee's report and then summarized in Chapter Seven. Struggles around data transfer, intellectual property (IP) rights, management of monitoring data, and providing realistic lifecycle modeling parameters during design are all retarding wider implementation of LCM approaches. The continued growth in the number, size, speed, and fidelity of numerical modeling and optimization approaches is also resulting in more pressure to develop solid data links, tool integration, and design methodology. Finally, while both risk and uncertainty remain topics of intense interest, relatively few risk or uncertainty approaches have been codified into rules, regulations, and design methodologies to date. This gap between what is desired for applied design and what has been demonstrated at a proof-of-concept level appears to be more difficult to bridge than first anticipated.

2. DESIGN METHODOLOGY

What actually comprises "design methodology"? Based on existing research literature in ship structural design, it is apparent that the term "design methodology" is used to denote several disparate aspects of the complete ship design process. One aspect is the procedural aspect of design, in which a design methodology prescribes a structured sequence of activities, starting with an initial statement of needs and ending with a design specification. An alternative interpretation of design methodology is related to the predominant performance goal that is the focus of the process, often captured in the term "Design-for-X" (DfX). Here, the "X" normally represents a specific goal such as operability, environment, safety, or production. A third aspect of design methodology relates to various strategies for handling the two-way mapping between the form space and the function space related to design, that is, identifying basic decision support methods that bring a designer from a set of needs and requirements all the way to a final design description. In the remaining sections of this chapter, each of these aspects will be discussed in more detail.

2.1 Developments in procedural aspects of ship design methodology

Perhaps the most well-known, classical design model is the design spiral, first presented by Evans (Evans, 1959). Though often used as a process description, the design spiral is often regarded more valuable as an abstract model, capturing the sequential, iterative nature of the design process. The spiral approach assumes a relatively smooth process of balancing out conflicting requirements. This idealization of the design process is challenged in recent studies of naval ship design processes, pointing to the fact that the design search space contains important regions of cliffs and plateaus in the functional relationships between core capabilities, size, and cost (Andrews et al., 2012b). Further, the design spiral is generally criticized for locking the designer into his first assumptions. As a consequence, the "System-Based Design" methods (Levander, 2006) have emphasized the development of a functional structure transforming the customer needs and high-level requirements into a relatively detailed definition of specific functional requirements. In this way, the specification of form elements is postponed until a fairly well balanced solution can be proposed. This follows the basic principles of the German VDI-model (Pahl et al., 2007) and has been applied to many ship types, predominantly cruise vessels, ferries, and most recently, offshore service vessels (Erikstad and Levander, 2012). More recent additions include the building-block design proposed by UCL (Andrews, 2003a) and methods adopted from the systems engineering domain, such as the Responsive Systems Comparison method (Ross and Rhodes, 2008).

Other process models put more emphasis on the creative and innovative elements, especially in the early design stages. There has been a discussion whether stringent methodologies and advanced tools will set new constraints, rather than enhance innovation, (Koelman, 2013) on lines generation. Also, the general availability of 3-D prototyping in the early stages is likely to influence the choice of design process. These models might, on the one hand, lock the designer into first assumptions, while on the other hand, provide a platform for a visual, fast-feedback "design sketching" environment (Alonso et al., 2013, Koelman, 2013) in which the designer's experience and preference for "design style" can be expressed (Pawling and Andrews, 2011). By connecting parametrically defined building blocks in the 3-D model with their corresponding functions in a system-based model, changes in customer needs and functional requirements can be seamlessly forwarded to updates in one or several design templates (Erikstad and Levander, 2012). This can be further combined with decision support systems for space configuration, layouts, and arrangements, using both spatial (Oers, 2011) and non-spatial models as well as topological models (Gillespie et al., 2012, Parker and Singer, 2013).

2.2 Developments in "Design-for-X" and risk-based design

A summary of the most recent developments related to the design for specific performance aspects, also known as "Design-for-X" (DfX), is given by Andrews et al. (Andrews et al., 2012a). From a structural design point-of-view, the most relevant DfX aspects are design-for-production and design-for-safety. Both of these will be handled separately later in this report. Furthermore, design-for-environment and design-for-energy-efficiency have received considerable attention the last few years. In Hirdaris and Cheng (2012), a number of alternative technology options are reviewed, and DNV looks into different options for CO_2 reductions (Hoffmann et al., 2012).

In general, DfX's concept puts the emphasis on the performance achievement, and, at least in principle, has no specific requirements towards the specific design solution or the design process to be followed. Thus, DfX is closely related to the current trend towards goal-based design methodologies in general (Vassalos, 2012), and risk-based design in particular (Lee et al., 2010, Boulougouris and Papanikolau, 2013), endorsed by recent International Maritime Organization (IMO) regulations.

IMO and the merchant maritime industry have made advances in proposing safety standards for merchant ships by adopting pro-active safety measures for future rules and regulations in the frame of a holistic approach to ship's safety. IMO and International Association of Classification Societies (IACS) decided to move from prescriptive concepts to probabilistic assessment methods and goal-based standards (GBS). Therefore, a risk-based approach and its assessment methods have become important design tools, especially in the shipbuilding industry, by facilitating the accomplishment of safety objectives in a cost effective manner. A risk-based approach is generally recognized as a proactive and rational method for handling the safety and environmental issues as well as enabling accelerated innovations and the introduction of new technologies in ship design. As some on-going research efforts continue in this regard, the risk-based ship design approach is applied to new concept container vessels and CO_2 carriers, and from this, standardization framework for risk-based ship design is proposed, as shown in Figure 1 (Lee et al., 2012a).

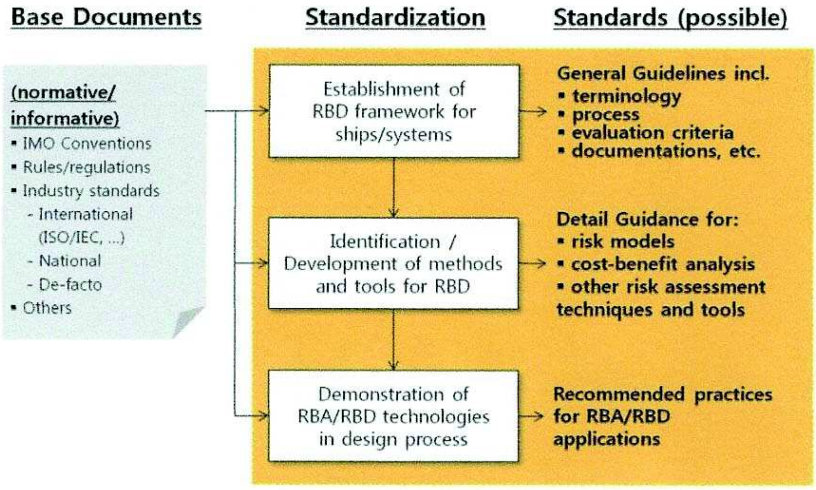

Figure 1. Proposed standardization framework for risk-based ship design (Lee et al., 2012a).

Currently, there are challenges, especially for the maritime industry, to cross the bridge from rules-based to risk-based design. This means that, although there are near enough scientific and technological research findings available for risk-based design to be fully implemented in the maritime industry, industrialization of processes, design tools, techniques, data, regulations, and approval still require careful attention. This implies that the implementation of the risk-based design in ship design requires a lot of time and efforts. Additionally, perhaps most importantly, the actual need of a risk-based ship design approach must be accepted by all stakeholders in order to facilitate the transition from prescriptive to goal-setting regulations. A practical example of the application of a risk-based design approach in the design of a cruise ship is reported in Vassalos (2012). Here, risk-based design is understood as the integration of risk assessment in the ship design and decision-making processes, as shown in Figure 2.

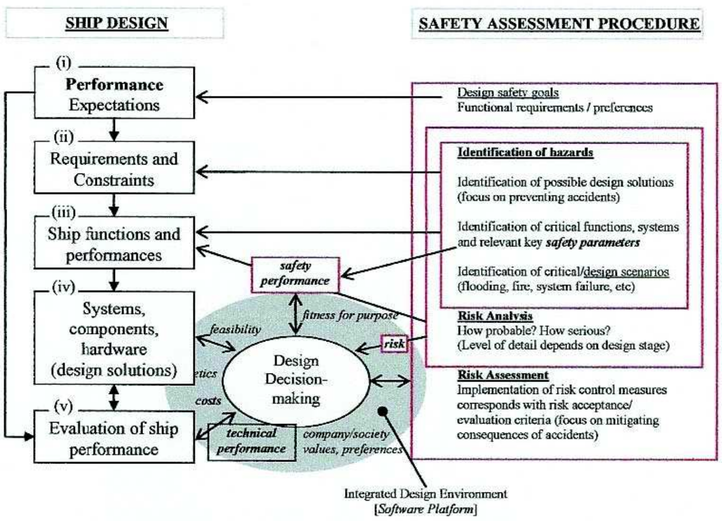

Figure 2. A high level framework for risk-based design (Vassalos, 2012).

Risk is the product of the frequency of an event and the associated consequences. Risk-based design approach is an improved alternative to the traditional design process, as it integrates safety as additional design objective. Thus, the designer has to justify that the risk of any feasible design is less than or equal to the specified acceptable risk. Risk categories, such as system failure, human life, environment, or property, can be varied, and these are treated separately. The total risk is obtained by the sum of partial risks from different damage categories such as explosion, fire, collision, and grounding. Each partial risk can be computed with the aid of risk models like Fault Tree Analysis (FTA), Event Tree Analysis (ETA), or Bayesian networks.

Risk-based design concept is applied to the assessment of the damaged stability of a generic navy vessel. In this study, numerical simulation tools are implemented in modern risk-based assessment methods for assessing risk after flooding. Survivability of the vessel is calculated using a mathematical risk model, and as a result, an attained survivability index can be calculated and used as a reference for setting the acceptable risk level (Boulougouris and Papanikolau, 2013). Risk-based approach is also used to generate the risk matrix of an LNG cargo handling operation. A hazard analysis of the LNG cargo handling devices, such as valves, the piping system, and the control system, is performed prior to risk analysis. Using the results, maintenance, and operational recommendations for reducing probability of failures of LNG cargo handling devices are presented (Roldan and de Souza, 2012).

The risk-based design project RISPECT (Hifi et al., 2012) provides a methodology that combine a detailed analysis of long-term experience from a large number of ships with reliability or risk-based methods to work out useful and justifiable risk-based inspection plans. The goals of the project are better inspections, the detection and repair of more important defects, fewer pollution incidents, and the savings of lives. The RISPECT inspection planning tool is intended to be used by the shipping industry. It aims to combine the traditional experience-based, class rule driven inspection method with first principles, reliability based, and inspection methods. By developing this combination it aims to demonstrate an improved decision making method for safe, cost-effective structural inspection and repair of existing ships.

The use of advanced computational tools allows the quantification of the risk level of a particular design and its exhaustive comparison with alternative designs. In this aspect, risk is no longer a constraint but a measure of safety performance and design objectives, which can be used in an optimization procedure. This can become optimal ship design for minimum risk, having rational efficiency and economy computational performance. For example, the lifecycle structural optimization of the midship section of a double hull tanker, considering multiple risks such as oil outflow, CO_2 emissions, and failure, is performed (Kawamura et al., 2013). In this case, the lifecycle benefit is used as the objective function of the optimization, in which the various risks are evaluated as a part of the lifecycle cost.

There are research outcomes from the risk-based approach which contribute to the implementation of risk-based design methodology in ship design. From them, the safety assessment process, based on previous design process, supporting tools, and standardized framework, will help to establish risk-based design concept and advance the safety level of the new types of ships. Such benefits can be obtained for environmental protection as well as promoting the development of safety level approach based goal-based standard from IMO. Related to this, one of the research outcomes is the introduction of a time-based ship safety assessment model (SSAM) and SSAM-based safety assessment framework as a supplement to use the IMO formal safety assessment (FSA) and the gains of SAFEDOR (Kang et al., 2012). From IMO FSA, it is possible to obtain a balance between the various controversial, technical, and operational issues. From the SAFEDOR project, the meaning of a safe ship design has been clarified. The SSAM describes a ship's mission-based functional hierarchy including not only functions, systems, and subsystems but also their environmental context, organizational and management infrastructure, personal subsystems, and technical/engineering systems on a time basis. Safety assessment framework can be used for safety assessments and for selecting the best risk control options for a novel ship design if designers have an objective and concretized generic model.

Reliability-based approaches to the marine industry are active to support and provide one of the fundamental elements of the risk-based ship design capability.

In case of subsea applications, the reliability assessment of subsea pipelines is conducted to prepare their risk assessment procedures and related decision making processes (Gazis, 2012). Also, the reliability-based load and resistance factor design (LRFD) method-based composite pressure vessel design procedure for subsea blowout prevention is studied. Target reliability is set to establish LRFD-based composite pressure vessel code. It determines the probability of failure of the vessel subjected to external hydrostatic pressure (Cai et al., 2011).

For naval applications, the probabilistic approach is used for naval ship structures to build integrated lifecycle maintenance, monitoring and managing under the uncertainty of multiple and conflicting objectives (Frangopol et al., 2011). Efforts are also made to reduce the uncertainty in the performance assessment of ship structures by updating the wave-induced load effects with the information acquired from structural health monitoring. The reliability analysis is performed with respect to the midship cross section of the Joint High Speed Sealift (Zhu and Frangopol, 2013, Zhu and Collette, 2013)

For ship structural material and member cases, the probabilistic approach is used for composite laminated structures, aiming to find optimal use of them in non-high speed light craft (Sanchez et al., 2011). A reliability approach is used to conduct the ultimate strength assessment of aging steel plates subjected to compressive load and randomly non-uniformly distributed corrosion wastage. In this study, the reliability of a series system composed of two time variant events, corrosion deterioration and ultimate strength assessment of a rectangular plate is studied. It was assumed that the correlation between them was unknown (Silva et al., 2012). The Bayesian network and a reliability approach are utilized, and as a result, a new reliability purposed dynamic algorithm for the Bayesian network is presented to deal with the fatigue cracking problems of the stiffened panels (Zhu and Collette, 2013).

For offshore applications, a rational reliability assessment procedure for hull girder ultimate strength assessment of ship-shaped FPSOs is investigated. Four ship-shaped FPSOs are considered as the case study, and the effect of the return period of VWBM, environment severity factor, and corrosion effects on hull girder reliability index are investigated (Chen et al., 2013b). Also, a methodology for fatigue reliability-based design optimization with respect to bending stiffener, the key structural member of umbilical/flexible risers to protect the upper connection against damage from over-bending, is introduced (Yang and Wang, 2012).

Implementation of HiP-HOPS in the reliability and availability analysis of ship machinery systems, such as propulsion and electric distribution systems, are studied (Ruede et al., 2012). Here, HiP-HOPS is a compositional, model-based safety analysis technique. Use of HiP-HOPS permits the rapid evaluation of multiple design variants and design modifications, especially when compared to the development and analysis of fault trees separate from the graphical system model.

2.3 Developments in ship form-function mapping, tradespace searches

Fundamentally, the concept of design can be defined as a mapping from the function space that defines needs and requirements, to a form space containing the description of the final design (Coyne et al., 1990). The function-to-form mapping is a fundamental aspect of design and is sometimes contrasted to engineering analysis, which is fundamentally aimed at the opposite process of deriving the function (performance) from a given form (description).

To support this mapping, from needs and requirements to preferable solutions in the design space, there are several competing strategies. One is optimization, where heuristic and nature-inspired methods in particular, such as genetic algorithms, ant-colony optimization, and simulated annealing, have received much attention (Collette, 2014). Optimization methods will be discussed later in this report.

An alternative approach is set-based search strategies (McKenney et al., 2011, McKenney et al., 2012). Set-based design has been combined with a rule-based configuration for arrangement optimization in the conceptual stage for both naval and offshore vessels (Oers et al., 2007, Oers, 2011). Designing ships “inside-out”, the importance of functional development (Keane, 2012).

Since the failure of artificial intelligence to live up to its expectations in the 1980s and 1990s, we have recently seen renewed interest in using knowledge-based systems in the design process. In the work of Cui and Wang (2013), experiences of design experts, design rules, and successful previous designs are stored in a knowledge base. Other contributions are intelligent arrangement design for naval vessels (Daniels et al., 2011), knowledge-based systems used in structural design (Yang and Wang, 2012), and a prediction model based on neural networks, which is trained with data of optimized structural arrangements and is capable of estimating the structural properties for different hull geometries (Chaves et al., 2014).

From a design perspective, the form-to-function mapping is basically about analysis methods that allow for a fast and efficient, yet accurate, evaluation of specific design alternatives as part of an overall design process. Throughout the last decade, these analysis methods have developed considerably, where high-fidelity, first principles tools, such as computational fluid dynamics (CFD) and advanced finite element analysis (FEA), have moved from the research institutions to become an intrinsic part of everyday design processes. Fundamentally, there is a tradeoff between the fidelity level of the model and resource expenditure. This corresponds to a more fundamental tradeoff between breadth and depth in the search for design solutions and is thus an intrinsic part of the design process (Zheng et al., 2013). From a normative perspective, one should generally start with lower fidelity model in the conceptual stage (go broad) and then migrate towards higher fidelity models in the detailed design stages (go deep). However, maintaining a rational approach to this tradeoff throughout the design process is often difficult since we have few explicit, quantitative measures of these tools and model properties. The wide adoption of CFD and FEA tools has contributed to a tendency towards too high fidelity models in the early stages, thus missing potentially preferred solutions in other parts of the design space. Empirical prediction methods that have proved their usefulness for decades, such as Holtrop and Mennen resistance prediction methods or Schneekluth’s weight approximation methods, have not been updated for several decades (Koelman, 2013).

To alleviate this situation, there are two main strategies available. The first strategy is to shift the Pareto frontier that represents this tradeoff outwards, for instance, by allowing the more efficient, seamless integration of high fidelity tools into CAD software (Yu et al., 2012, Cui and Wang, 2013, Roberts et al., 2013); or by allowing more efficient searches through the design space, simply by updating key empirical methods; or by applying surrogate modeling methods (Collette, 2014, Prebeg et al., 2014), including response surfaces (Pajunen and Heinonen, 2013, Chaves et al., 2014), and experimental design methods (Zheng et al., 2013).

An alternative strategy is to support a better-informed balance between model fidelity and resource expenditure by associating available tools and methods with relevant metrics. One example of this is the hydrodynamic optimization of catamarans regarding the choice between high fidelity (URANS) and low fidelity (potential flow) methods.

A somewhat different approach to using simulation for analyzing system performance is to use discrete event models that capture the complex operation of a ship. These have been used for both deriving a more detailed and realistic operational profile for the vessel (as opposed to idealized design cases), as well as for aggregating lifecycle performance measures such as energy efficiency, operability, and safety. This will typically call for an extensive modeling of the operating context of the vessel such as metocean, fleet logistics, and ice. This approach has been applied to the design of LNG transport (Erikstad and Ehlers, 2014), arctic transport (Bergström et al., 2014), the design of ships in rouge sea states (Bitner-Gregersen and Toffoli, 2014), and for ship transport energy efficiency (Coraddu et al., 2014). This reflects a general extension of system boundaries, analyzing ship performance as a part of larger operation or a fleet/logistic chain (Andrews, 2003b, Hagen and Grimstad, 2010, Ulstein and Brett, 2012).

2.4 Handling uncertainty in future operating context

When designing ocean engineering systems, such as ships, platforms, and transportation services, there is a considerable degree of risk and uncertainty related to key aspects of the system's future operating context. The total size of the market is highly dependent on external exogenous factors, such as GDP growth rates and oil prices, affecting both the size and structure of the market as well as freight and day rates. Future environmental regulations, in particular, the location of emission control areas, will be important for the selection of fuels as well as other emission controls; and rapid technology development may render design solutions with non-optimal configurations non-competitive after only a few years.

Thus, the design of a new vessel needs to strike a balance between optimizing the vessel for the (likely) first contract or trade entered, while investing in additional functionality and performance capabilities to meet future requirements and changes in its operating context. This could be increased fuel prices, stricter environmental regulations, or new and more cost-efficient technology in more northern and deeper waters. To further add complexity, these additional capabilities might either be made part of the vessel at the design time, or they may be provided as design options, to be executed depending on information that will only be available in the future. Thus, there has been a need for developing efficient methods to be used for the conceptual design of innovative ship solutions, able to deliver sustained value to stakeholders over time in a complex, uncertain, and changing lifecycle.

Though shipping markets have always been volatile, the traditional approach in marine design has been to assume a fixed set of requirements to which the final design must comply. To the extent that alternative scenarios for the future operating context have been considered relevant, the most common response has been to design towards the most likely scenario and subsequently analyze the sensitivity of the final solution towards variations in key operating parameters.

This is not to say that flexibility is not being valued in the maritime sector. We have seen many examples of versatile vessels able to serve multiple cargoes, services, and markets. OBO carriers, car carriers with hoistable decks, and offshore vessels with multi mission capabilities are typical examples. To some extent, vessels and systems are designed with additional capabilities that go beyond the immediate requirements. This implies hedging towards changes in the operating context that may render the vessel less competitive in the future while at the same time, providing a level of specialization that can be a liability in a second-hand market that puts a premium on standard solutions. Also, options are routinely provided as parts of specifications and build contracts, setting a predetermined price on changes that may be exercised in the future. However, the quantitative valuation of flexibility and options is a challenge, both with respect to determining the optimal capability level, the price of options, and for conveying the operating value of these additional capabilities and options to prospective customers. Thus, the approach taken today can best be described as predominantly a "gut feeling" approach by key decision makers.

Methods for quantitative risk management was first developed in the financial sector, used to design client portfolios with a predetermined risk profile. This was further developed into a theory for pricing financial options, using the Black-Scholes formula to determine the time-dependent option price (Black and Scholes, 1973). The financial market approach to handling uncertainty and risk was later adapted and applied to engineering systems using real options analysis. Real options made it possible to put a value on future opportunities to change or expand the capabilities of a design, switching between markets, or retrofitting components and technology. In the shipping sector, real options analysis has been used, for instance, for the valuation of combination carriers (Sødal et al., 2008), the analysis of options in shipbuilding contracts (Høegh, 1998), and naval ship design and acquisition (Gregor, 2003).

An alternative path for design decision-making under uncertainty is stochastic optimization. This approach extends a more traditional deterministic optimization by explicitly modeling alternative future scenarios and corresponding probability distributions, and then explicitly taking into consideration opportunities to change the design or project at later stages (two-stage/multi-stage models). Marine technology applications include the design of emission controls for ships (Balland et al., 2013), uncertain environmental policy (Niese and Singer, 2013), and vehicle routing problems (Fagerholt et al., 2010). Further, the proposed research area will share important characteristics with the emerging field of "Risk-Based Design" (Papanikolaou and Soares, 2009) in taking a probabilistic approach towards modeling future events and scenarios (Wagner and Bronsart, 2012).

A broader engineering systems perspective on designing for flexibility is provided in the book *Flexibility in Engineering Design* (de Neufville and Scholtes, 2011). Here, a combined theoretical and practical framework is provided for identifying, analyzing, and implementing flexibility in a broad range of large-scale engineering systems. Other work has integrated design for flexibility and real options evaluation as part of a more complete systems design process (Ross et al., 2008, Beesemyer et al., 2011), which has further been adapted to ship design (Gaspar et al., 2012).

3. DESIGN TOOLS

3.1 Introduction

The number of available computer design and analysis tools available to the naval architect has expanded since the preceding ISSC Congress assembled in 2012. Several trends impact the development of such tools. There is a persistent desire to increase the fidelity of modeling throughout the design process while simultaneously trying to push such high-fidelity modeling into early stages of design. At the same time, recognition of the value of the digital models created by such design tools is growing. Efforts continue to leverage this value by making data from such models available in new contexts, including in the shipyard and throughout the vessel's service life. Finally, there is a struggle with fragmentation of such tools as their number and focus expand. The combination of these factors has driven both feature addition to monolithic design software packages and classification society toolsets as well as long-term investment in more distributed architectures. In turn, this has continued to support investments in data exchange formats for use during and after the vessel's design is completed. Implementation of concurrent engineering approaches has made design data available on the shop floor via lightweight viewers and augmented reality devices. These developments are reviewed in this chapter.

3.2 Development of design tools

During the time since the last ISSC Congress, the overall state of computer-aided ship design (CASD) in the marine industry has been reviewed by several authors. A recent review has been presented on the underlying numerical techniques used in hydrodynamics, structures, and production simulation (McNatt et al., 2013). More applied reviews have also been published, including one focused on the engineering simulation tool used primarily within the GL Group (Bertram and Peric, 2013) and a review of the MAESTRO code and history of computerized ship structural design (McNatt et al., 2013). A special issue of the journal CAD was also produced, highlighting in-part developments in structural design and outfit/production planning via design tools (Kim et al., 2012). As shown in these works, continued development of high-fidelity simulation and smooth data exchange between different software packages and different phases of the vessel's lifecycle remain key focus areas for the marine industry. The continued use of increasingly detailed simulation in structural design, with extensions into collision, fire, and blast simulations, is expected in the future. A key challenge in industrial projects is in ensuring that an appropriate level of modeling is used, supported by necessary experts in conducting such modeling.

The widespread adoption of advanced simulation methods in design has also resulted in a number of shortcomings being identified to date. Notably, continued unhappiness with the industry-standard NURBS modeling of hull surfaces remains (Koelman, 2013, McNatt et al., 2013), owing to complications ranging from handling complex geometry to mathematical limitation in the NURBS formulations that make automatic data processing difficult. A method of handling this complex surface information for automated finite element meshing was recently presented (Wang et al., 2014), highlighting both the power and complexity of NURBS. Despite these misgivings and the development of other approaches, such as subdivision surfaces and T-splines, no clear alternative has been established. Several authors have also noted in general terms the challenges of the increasing number of often-fragmented design approaches (Ulstein and Brett, 2012, Koelman, 2013) and the growing concern that the increased focus on analysis is producing minimal returns in the performance of the design (Ulstein and Brett, 2012). This echoes the concerns raised in the conclusion of Bertram and Peric (2013), where the case for a careful blend of appropriate modeling strategies and expert users is noted.

The past three years have seen extensive development in linking multiple design tools together to conduct a more comprehensive structural evaluation of new ships and offshore structures. These approaches have involved both distributed concepts, which included the linking of independent programs into a larger framework, and the monolithic program concept, where development of a monolithic program that handles several linked calculations for a specific vessel or platform type was attempted.

Both approaches involve tradeoffs. In the distributed approach, middleware is needed to link existing codes together and handle data translation, and often times some type of data processing such as interpolation to transfer CFD loads to finite element models. Such middleware takes energy to create and maintain, and deep linking into the data structure of the individual programs is often not possible. However, developing monolithic tools often requires re-creating existing analysis and simulation capabilities, which can be cost-prohibitive. Thus, it is not surprising that the reported new monolithic tools appeared primarily for newer areas, such as wind turbines (Thomassen et al., 2012), where long-standing, existing analysis packages may not exist.

Several ongoing efforts at creating the middleware for distributed approaches have been updated in the past three years. The Lloyd's Register DIME (Data Interface Management System) is one proposed middleware approach that was reviewed in detail in the 2012 Committee IV.2 report. This system allows translation between complex CAD/CAM ship product models, and it meshes and simplifies the geometry required for analysis calculations through a mix of semantic and geometrical processing routines. Recent extensions to new naval ship design tools in the LR/MARTECH suite have been reported (Pegg et al., 2012, Roberts et al., 2013) along with additional information about DIME. An online middleware solution for small and medium Korean shipyards was also presented (Shin et al., 2012). In this case, a web-based system linked together databases of previous designs, hull form modifications, calculation tools, and design information management. STEP AP215 output is planned for this system in the future. Nupas-Cadmatic is working on a "building block" approach capable of linking many different codes in a product data model that is focused on both re-use of previous designs and support for a shipyard company with multiple shipyards around the world (de Jonge and Kramer, 2014). Nupas-Cadmatic notes that they explicitly support the distributed tool vision in this architecture.

An area where such linkage has been particularly active is linking the output of either 3-D potential flow codes or CFD codes to finite element analysis. This presents a challenge as the mesh domain in the fluid is either usually substantially larger (potential flow) or smaller (viscous flow) than a global FE model of vessel, and thus, an interpolative framework is necessary in addition to raw data translation. Recent advances in this area from both the Maestro code (McNatt et al., 2013, Zhao et al., 2013) and within the GL group for the next generation of large, flexible containerships have recently been presented (Payer and Schellin, 2013) as well as a similar shipyard-based approach for fatigue (Won et al., 2013). In general, these approaches are built into marine-specific structural tools, although middleware translators can be used to couple to generic, finite element packages.

Bespoke and one-off middleware solutions also appear frequently in publications and have been shown to provide encouraging results for complex design studies. These approaches typically build off of published program APIs or standard file structures such as XML files. Such published interfaces make the creation of custom middleware more cost-effective. Zanic demonstrated a decision support framework by linking CAD/CAM code NAPA Steel with the analysis code Maestro and the optimization code Octopus for the design of small, open-topped general cargo ships (Zanic et al., 2013c). Danese and Aasen (2013) presented an approach to tracking weight data across distributed design, purchasing, and other enterprise activities with ShipWeight, noting that a distributive approach is often necessary, as all-in-one software for naval-specific CAE applications are lacking. At a more detailed level, Ruy et al. (2012) developed a Python-based automated system to request cut-outs in structural members and run distributed systems using Tribon M3's API. In this approach, the outfitting engineers can request specific cut-out locations and topologies. These requests are tracked and forwarded to the hull structure group who can approve the location. Then, the cut-out is automatically added to the ship product model. Similarly, Rox and Astrup (2013) reported on an XML-based approach to link the initial steel design in the German design package E4 to rule-approval in DNV's Nauticus Hull. Liu and Jin (2012) reported on linking Tribon to other CAE applications via Tribon's XML file. Such industry-specific custom solutions clearly continue to be an important component of the ship design information flow. All the solutions mentioned here make extensive use of standard technologies for interfacing (e.g. Python API scripts, SQL databases, XML), which indicate the value of including standard data storage routines, even in custom software.

Feature extraction from CAD/CAM databases for analysis remains a topic of interest for the industry, especially for costing approaches. Recently, Caprace (2011) proposed a novel, bottom-up, feature-based costing approach for vessels that relies on automatic extraction and identification of structural features, such as cut-outs, weld lines, and bevels, from CAD/CAM data. With the expanding use of such modelling in early stage design, it is hoped that such an approach can provide more realistic costing earlier on. Critically, if such a system can be automated or moved to near-real-time, cost feedback can be given to the designer to reduce the cost of proposed structures during the design stage. Similar work was also reported in Japan (Goldghate and Yamaguchi, 2012), with a system for tracking design throughout the shipyard design process.

Structural fatigue assessment is a complex design task, especially when the direct-calculation spectral method is used. In this case, stress RAOs for all the fatigue-critical structures must be determined for numerous speed, heading, and loading combinations via linked seakeeping and FEA models. Then, fatigue calculations must be made over a wide range of operating conditions. While basic guidance on this calculation and some software support have been available for over a decade now, usage has not been widespread. Primarily, the complexity and difficulty of the calculation, even with existing tools, have been noted as the reason for this situation (Elsen, 2013, Hunter et al., 2013, Won et al., 2013). Not surprisingly, efficient spectral fatigue design tool development remains a subject of interest. Recently, Won et al. (2013) reported on a shipyard-specific tool for conducting spectral fatigue assessment of proposed vessels that intentionally provides limited options and flexibility, compared to existing classification society packages, to reduce both analysis time and the chance for analyst error. In addition to automating the load-to-FE-model transfer process as noted above (McNatt et al., 2013, Payer and Schellin, 2013, Zhao et al., 2013), this code automates much of the hot-spot stress calculation procedure for numerous structural details, and it contains as few user-settable options as practical to ensure a fast, consistent application of the yard's fatigue life methodology. The MAESTRO suite has also been extended to support fatigue calculations, with a detailed overview of the new calculation procedure and example presented at COMPIT (Hunter et al., 2013). GL also reported on a "re-engineering" of their spectral fatigue toolchain that removes friction points and difficult operations to reduce the time required for analysis (Elsen, 2013). Another approach attempted is to simplify the method, on which Chen et al. reported. Relying instead on a simplified procedure from DNV (Chen et al., 2012), this development dispenses with the fine-mesh FEA component of the analysis. Notably, all of these publications do not focus on increased fatigue assessment accuracy or fidelity as their primary contribution, but instead promote ease-of-use.

While much work of the past three years has focused on code linking and automation, development of stand-alone structural design tools continues. Primarily, these are simple tools designed either for rapid feedback during early-stage design or for helping with specific structural tasks where data re-use and integration is less critical. Addressing early stage design, Stenius et al. (2011) reported a simple, rule-based approach for developing minimum weight designs for high-speed craft. This was used to compare a number of steel, aluminum, and composite concepts during the early design stage and to quantify the weight impact of structural configuration and material choices. Yang and Wang (2012) reported on the development of a knowledge-based engineering (KBE) system to perform efficient design of deck structures. Making production decisions easier and more informed, Dong et al. (2012) proposed a simple, math-based producibility evaluation approach for titanium structures. BVB Café is a more comprehensive stand-alone tool. While it has links to several external solvers for 2-D CAD drawings and FEA, it primarily attempts to provide a more efficient geometry-to-structure CAD solution. Further developments with this code have recently been highlighted in COMPIT 2014 (Zagkas and Bralic, 2014). Given the increased focus on distributed solutions, it seems clear that stand-alone tools can grow in concert with more integrated design approaches by following the lead of programs such as BVB Café.

3.3 Tools for lifecycle cost modeling and lifecycle assessment

Reports of successful tools for lifecycle cost (LCC) modeling and lifecycle assessment (LCA) of environmental impacts remain sparse. This is at odds with the increased level of interest being generated around each of these topics. A further discussion of LCC and LCA approaches proposed during the past three years is contained in Chapter 6 of this report. ABB reported on a large effort to bring design prediction to onboard decision support tools and return the link to the owner's office via fleet analysis (Ignatius et al., 2013). Aspen et al. (2012) reviewed current lifecycle assessment tools available to the marine industry and carried out a case study demonstration on a longline fishing vessel. This study concluded that much work remains to be done to move LCA into a practical method for vessels under construction, including better system boundary standards, industry-specific assessment databases, and tighter integration into ship design software. Overall, while both LCC and LCA continue to gain traction, there is currently a gap between the capability of easily-available tools and the desire to address these topics.

3.4 Links between design tools and production and operational phases

The enormous value represented by digital vessel design models and databases created during ship design and construction continues to attract attention for data re-use over life. Much progress has been made for data re-use within the constructing shipyard (e.g. Morais et al. (2014) presents recent progress with ShipConstructor), but struggles remain to make this data available over the vessel's entire lifespan. One major issue in sharing such data is the fact that the intellectual property associated with the majority of this data is normally owned by the shipyard who does not want it to fall into the hands of competing yards. Further complicating matters, the building yard typically has the shortest temporal interest in the vessel, especially when compared to the vessel's owners, flag states, and classification societies. Thus, while this section does report notable progress over the last three years in this area, there is still no industry-wide agreed approach for handling ship design data over the vessel's lifecycle.

The ability to view 3-D product data over the entire vessel's lifecycle continues to be a fairly basic requirement of any design-model use. Several proposals have been developed for lightweight viewers, typically independent of the underlying CAD/CAM/CAE system that stores the full design model. Notable progress has been made with Siemens "JT" lightweight open viewing format. This format was codified in ISO Standard 14306:2012 in December 2012. While its applicability far exceeds the marine field alone, as of 2014, several major marine players served in the corporate program group for JT including Electric Boat, Hyundai Heavy Industries, and ThyssenKrupp Marine Systems. Marine progress with JT was reported in several venues, including RINA's Naval Architect (Malay, 2012), and JT was adopted for an NSRP visualization pilot for the common parts catalog in the United States (Electric Boat, 2013). A rival approach was presented by ShipConstructor, whose Autodesk compatibility allows direct tie-in with the Navisworks suite, which is widely used in other industries (Larkins et al., 2013a, Larkins et al., 2013b). In marine-specific software, Nupas-Cadmatic reported on efforts to use 3-D models directly on the shop floor to replace 2-D paper drawings via a variety of viewers (Cadmatic, 2012). While vendors are clearly leading much of these efforts to date, some vendor-neutral efforts have also been attempted including a Dutch effort to create a vendor-free, simple, 3-D visualization package (Asmara et al., 2012). The use of such lightweight models for production interference checks has also been proposed (Suh et al., 2013), indicating that some calculations that occur down-stream from engineering may also migrate to such platforms in the future.

Augmented reality (AR) approaches, where the visualization of data from the ship product model is linked to viewing the actual structure, are rapidly growing extensions of these visualization approaches. At the simplest level, an early study reported on using embedded RFID tags in the structure and equipment itself to help locate the user in the 3-D model and associated design data (Lee et al., 2012b). More recently, Halata et al. (2014) presented a detailed account of the design and prototype of an AR approach for outfitting tasks such as pipe installation. Based upon extensive observation, information needs were investigated and divided into three categories. A prototype AR device using an Android tablet was implemented and used in a production environment. Post-use survey results were gathered with largely positive feedback. Matsuo and Shiraishi (2014) reported on two AR demonstrations. The first demonstration integrated on-piece markers, laser scanners, and an AR tablet to track progress in shaping curved hull plates. In this approach, the current shape of a complex curved plate is compared to the desired final shape, and the differences are displayed to the shop floor craftsman to help plan the next forming operation. In the second application, an AR approach is used to plan final pipe connecting runs. Here, the details of the final pipe run are not in the ship product model. Instead, the AR device examines the location that the pipe must be run though and determines how the pipe must be shaped. Future work will link the as-built pipe information back into the shipyard's drawing system. Helle et al. (2014) presented some initial results of a 2-year AR study in Finland using a Windows 8 tablet/phone AR device that located itself by using both visual cues and RFID tags on the vessel. Helle et al. explored two sample use cases with this system. The first was documenting vessel construction by adding virtual notes to a ship product model from the device during inspections. The second was requesting new structural cut-outs complete outfitting whose routing information was not complete when the structural steel was initially fabricated. All three AR approaches combined a variety of off-the-shelf AR software packages and existing mobile devices, and they are targeting similar, but distinct, steps in the vessel construction process.

In addition to viewing, more direct model exchange and keeping digital design models with the vessel throughout the vessel's life continues to be a goal of many owners and regulators. However, as mentioned above, there are serious intellectual property considerations associated with such data sharing. Thomson and Renard (2013) provide an overview of these issues, and highlight some proposed responses such as keeping some data ashore, separate from the ship, or allowing access to more data as the vessel design ages and the IP associated becomes less valuable. Naval applications are unique in this regard, as they offer an application where a single entity often owns or has rights to access all associated design IP and is the vessel's sole owner and operator. In this context, implementing through-life data solutions is much simpler, with only technical hurdles to overcome. The US Navy's Achieving Service Life Program (Anderson et al., 2013) recently demonstrated the use of a single FEA model throughout the vessels life, including aging-related updates for corrosion and fatigue life calculations. This paper indicated that such integration is indeed valuable.

While IP issues remain difficult, open standards for such data exchange continue to gain traction to bring this reality to commercial shipping. The ShipDEX extension to the S1000D standard for technical information is widely established for marine equipment manuals. The OpenHCM hull condition and thickness database is seeing more widespread use, including integration into major vendor packages, like Aveva and Sener, and classification societies such as LR, BV, and DNV GL. The integration with BV was recently profiled (Renard, 2012), and OpenHCM export has been added to the BVB Café software (Zagkas and Bralic, 2014). A key advantage of applications such as OpenHCM is that many of the IP-sensitive production details of the vessel can be removed because the full CAD/CAM model is normally simplified before exported into such a format (Thomson and Renard, 2013). To push this concept, Thomson and Renard (2013) advocate the creation of a "Model Repository File," or MRF, standard similar to the Ship Construction File standard to store more detailed digital models with access control built into the standard.

In addition to open standards, many vendors have released through-life extensions to their design-stage CAD/CAM/CAE packages. Most of these extensions attempt to offer a hub for through-life information that can interface both with the vendors own CAD/CAM/CAE packages and with other software or data structures that each ship owner may have. Complete all-in-one solutions seem to be less in favor, though some of the bigger, more general software packages attempt to offer such a feature set. PTC's CADDS 5 software integrates with a variety of PTC's through-life portfolio, including PTC's Optegra for viewing and integrated PLC data from CADDS 5 and other programs, and PTC's Windchill which is a more robust PLM solution for CADDS 5 and other data streams. The FORAN ship CAE database was reportedly integrated with Windchill (Penas, 2013) so that it could be used through-life. Likewise, SMART 3D, Nupas-Cadmatic, and AVEVA have their own "enterprise" packages capable of tracking digital design data throughout the vessel's lifecycle. Siemens recently highlighted the difference between marine-specific PLM models and more general PLM systems and proposed a new way forward to receive the benefits of each type of PLM system (Bresler et al., 2013) following the general trend discussed in this paragraph.

3.5 Developments in integrated naval architecture packages

The development of monolithic naval architecture packages continues, with new features and capabilities added to many of the existing packages used around the world. By enforcing tight data model coupling, such packages can offer easy transferability between different structural and production tasks as well as other naval architecture disciplines such as hydrodynamics and stability. A description of the major packages was presented at the last ISSC Congress in 2012 and will not be repeated here; however, the major packages have been summarized in Table 1. Specialized software for classification society analysis, approval of structural designs, and links to the rest of the product lifecycle from classification society databases have been selected for special review in Chapter 5 of this committee's report.

Table 1. The number of officially reported plaque cases in the world.

Name	Structural Modeling Capabilities	Website (as of Fall 2014)
Autoship	Structural member definition via SQL/AutoCAD approach, nesting, lofting.	cadcam.autoship.com
AVEVA Marine	Integrated structural design and detailed design/production package, with other naval architecture features as well.	www.aveva.com/marine
BVB Café	Features easy definition of structure on top of imported geometry, basic calculations, and extensive FEM import/export.	www.bvbcafe.com
CADDS 5	PTC's discrete manufacturing CAD/CAM platform. Focused on detailed steel and outfitting design. Includes lifecycle links via PTC's Optegra.	www.ptc.com/product/cadds-5/
Design for Sea/ Catia	Specialized marine tools built into more general CAD/manufacturing software. Supports initial design, FEM analysis, and links to lifecycle applications.	www.3ds.com/products-services/catia/welcome/
FORAN	Comprehensive naval architecture package. Supports initial vessel design and structural detailing. Links to ship production and PLM management	http://www.senermar.es/
Maxsurf	Supports initial structural design and built-in FEM analysis with beam/plate tool Multiframe. Links to other disciplines such as seakeeping, resistance, and stability.	www.bentley.com/en-US/Products/Maxsurf/Marine+Vessel+Analysis+and+Design.htm
NAPA	Basic through detailed design and production, including pre/post FEM processing capability.	www.napa.fi
Nupas-Cadmatic	Marine-focused modelling suite with extensive tools for steel definition and production. Includes LCM links via its "eShare" module, which can also share design data from other packages.	www.nupas-cadmatic.com
ShipConstructor	3-D detailed design CAD/CAM model for structure and outfitting built on top of AutoCAD and SQL.	www.ssi-corporate.com
SMART 3D	Intergraph's latest iteration of what was originally Intelliship, then SmartMarine 3D. Supports detailed steel design and manufacturing, strong links to process and outfitting/piping from co-focus on plant design.	www.intergraph.com/ppm/default.aspx

4. OPTIMIZATION DEVELOPMENTS

4.1 Introduction to Design Support Systems (DeSS)

Modern optimization methods developed in areas such as naval architecture, aerospace, and mechanical engineering, are capable of validating innovative vehicle concepts as well as generating competitive designs for standard ship types. The report of TC IV.2 at the ISSC 2012 contains a section on the design requirements, mathematical models of required fidelity for design phases (concept, preliminary, and detail), basic taxonomy, and applicable optimization methods and formulations, including safety as design objective and other topics. The methods presented in 2012 help designers to achieve significant savings for the shipyard and the ship owner; increase deadweight; decrease the price and weight of construction steel; decrease production costs; improve lead times; increase safety (and robustness); increase savings regarding lifecycle cost (LCC) among other beneficial results.

In the last three years, we have seen further progress in methodology and hardware:

– *Large scale practical problems*: Inclusion of the designer's talent and heuristic knowledge is shifting the focus from the simple optimization problem to the design support (DeS) paradigm, where the optimization module is a utility, since the real quality of the design process is not based on the inclusion of all possible or available complex calculations. Rather, it is based on the interactive designer's exclusion of all unnecessary considerations. DeSS enables the designer to concentrate on the relevant design attributes used in his/her educated (supported) key decisions regarding the design characteristics.
– *Design Analysis*: Development of IMO GBS and related IACS Rules (CSR) as well as the emergence of new fast general methods for reliability analysis based on the dimension reduction method (DRM).
– *Design Synthesis*: Emergence of techniques of surrogate modeling, problem decomposition, and coordination enable the designer to handle large scale structural models (i.e. full ship models). For optimal performance, the development of synthesis models still needs to be closely coordinated with analysis models.
– *Hardware developments*: Computing power increases by increasing the number of CPUs or CPUs' cores. Novel frameworks can enable distribution of parallel computation sequences to both standard CPU cores and massive parallel GPU cores (e.g. *NVIDIA Tesla Kepler K20).*

Building off our report in 2012, this chapter starts with an introduction to the overall design procedure for large scale design problems. The growth in problem size implies application of the novel hardware developments (see Section 4.2) that are paving the way for novel design synthesis approaches in formulation of practical mathematical models. Those approaches will enable the application of more complex rules in optimization, including the following:

– IACS Harmonized Rules (H-CSR) for double hull tankers and bulk-carriers requiring 3-hold models for each hold to be approved, resulting in large scale multi-hold design optimization problems.
– Development of practical mathematical models that use safety measures as design objectives (not only as constraints), leading to socially responsible design practices.

This chapter is further concerned with developments of practical optimization methods (Section 4.3) applicable in design offices, solving manipulated multi-criteria design problems (Section 4.4) in an acceptable time-frame and applying it to the design tasks:

– Optimization for production cost (Section 4.5), important for the yard decision makers.
– Optimization for LCC (Section 4.6), important to owner and operator.

In the remainder of this introduction, the overall design procedure, embedded into the interactive design environment with optimization utility, will be briefly discussed. The design problem definition for efficient DeS (decision support), is presented in Table 2. This framework is intended to be a generic description of a structural optimization process. As computational power grows via improved computer hardware and parallelized codes, it becomes increasingly important to tie such optimization approaches into a formal decision support system for the designers. The overall problem is composed of three main steps: design problem identification, design problem formulation, and design problem solution. These steps descend in a hierarchy from high-level problem description to the details of computing a range of potential solutions to the problem. In brief, they may be summarized as following:

(1) Design problem identification (DPI) includes the identification of mathematical models (i.e. criteria function sets and their supports and domains). Efficient taxonomy is instrumental for precise and

concise, yet comprehensive, definition of the decision blocks (see Zanic et al. (2013c)). For the example of commercial vessels (Oil Tankers and Bulk Carriers), critical constraint functions values are taken from the set of design loadcases using CSR.

(2) Design problem formulation (DPF) implies IT-formulation of requirements defined in DPI. It also includes problem manipulation to develop the most efficient algorithm. The efficient solutions for large scale practical problems are best obtained if the mathematical design problem is formulated together with the associated solvable mathematical model (and the corresponding IT-modules to support the stakeholders in their design-related decision making). It combines an efficient design analysis model (AM) for response and evaluation assessment, and the synthesis model (SM) for subjective and objective decision support using optimization solvers as utilities (see Table 3).

(3) Design problem solution (DPS) requires the integration of the DPF developed or selected modules embedded into the interactive environment for the inclusion of the designer's subjectivity and heuristic knowledge to provide adequate support for the decision making (DM) process. In the DeSS interactive environment, DPS needs control modules (sequencers) and a set of GUI utilities.

Table 2. Design problem definition, including basic taxonomy (Zanic et al., 2013c).

DESIGN PROBLEM IDENTIFICATION - DPI (CONCEPTUAL LEVEL)
Determination of design objectives set **o*** and related measures of robustness/sensitivity set **rx*,** for selected set of design load conditions/cases **LC** and design descriptors **d ,** Selection of design variables' nv-tuple **x,** among the set of design descriptors **d**, with corresponding structural (often represented as finite) element Groups (xeG). Selection of design criteria functions **c** (constraints **g>0**, attributes **a**) with corresponding function supports ceG-s, geG-s, etc. Note that design objective functions **o** could be obtained from attribute functions **a,** for given direction of improvement (min, max).
DESIGN PROBLEM FORMULATION - DPF (ALGORITHMIC LEVEL)
Selection of two basic mathematical models and corresponding IT-modules: Design analysis model (AM) for technical (response, feasibility criteria) and economical evaluations (cost criteria, risk), see Table 3bc. Design synthesis model (SM) for objective and subjective decision making, see Table 3a
SM formulation (given AM) includes: Design problem manipulation into equivalent but mathematically more convenient form. Selection of solution strategies (e.g. solvers based on optimization techniques **Σ**, surrogates **Ξ**) for the manipulated problem (Section 4.3). Development of method for the final subjective selection of preferred design(s) among generated design variants in Γ modules, using **π** modules for sensitivity /uncertainty/ robustness analysis.
DESIGN PROBLEM SOLUTION - DPS (PROCEDURAL LEVEL)
Application of the design procedure with practical implementation of selected AM inbuilt into the SM interactive decision-making shell, see Tables 4 and 5. AM/SM utilities involved should enable the efficient synthesis (optimization and sensitivity modules, databases, graphics, etc.) possibly based on parallel processing due to the required workload and time available to the given design phase, see Table 3.

The design problem formulation must ultimately lead to a single solution, denoted preferred solution, being selected for construction. In this step, two design support approaches are possible, which are denoted as Pareto Supported Decision-Making (PSD) and Decision Support Problem (DSP) to signify their basic differences. PSD enables the stakeholders' educated selection of the preferred design based on the sequentially generated 'geographical map' of the Pareto frontier in the design space X (spanned by *nv* design variables, used for 'form' description, see Chapter 2 of this report) and attribute space Y (spanned by *na* design attributes or 'functionalities', measured by KPIs). DSP generates preferred designs along the designer's route in those spaces using knowledge engineering. Of these approaches, PSD is the more commonly used system to date. Zanic et al. (2013b) provides a comprehensive overview of the various Operational Research methods that can be used for tackling this problem, building on the work in the 2012 ISSC report of this committee.

While evaluation mapping is a direct procedure (getting criteria function values for given design variables), the inverse design mapping (getting values of design variables for the aspired levels of objective functions), implied in the design process, is entangled with many mathematical problems. They lead to different methods in operations research tailored to the characteristics of objective and constraint functions of the problem at hand with selected optimization solvers. Based on the design problem definition (Table 2), a sequence of standard optimization problem formulations can be developed by integrating IT-modules defined in Table 3. Corresponding IT-modules, embedded into the interactive design environment (see Table 4) are enabling the design process evolution and the development of efficient designs.

Table 3. Criteria implementation–IT modules (Pradillon et al., 2012).

	(2a) SYNTHESIS MODULES (SM)
Δ	= set of modules for the interactive definition of the synthesis (optimization) problem: selection of variables **x** (subset of **d**) and criteria fn's **a** and **g** via module **Ω**, problem decomposition and coordination;
Γ	= set of synthesis modules (GUI) in synthesis model (SM) for optimization (using preference data $\mathbf{P}^u$, $\mathbf{P}^v$ for subjective definition of utility and value fns **u** and **v**), designer interaction with the design process, filtering of designs and visualization of **X, Y,** and metric **M, L** sets/spaces. Output: normalized **m, l** values
Σ	= set of optimization solvers (e.g.: Multi Objective Seq. Linear Programming- (MOSLP), Fractional Factorial Experiments (FFE), Multi Objective Particle Swarm Optimization (MOPSO), Multi Objective Genetic Algorithms (MOGA), Evolution Strategy-Adaptive Monte Carlo (ES-AMC) , etc.) for generating Pareto frontier $\{\mathbf{x}^k, \mathbf{y}^k\}^{ND}$ by filtering designs in feasible subspaces $\mathbf{X}^{\geq}$ U $\mathbf{Y}^{\geq}$ based on objectives **o**.
Ξ	= surrogate solvers (e.g. Response surfaces (RS), Kriging, Radial Basis Functions (RBF), etc.) Input: set $(\mathbf{d}, \mathbf{z})^k$ for fns c_i, Output: quality measures q_i for selected data in data container $\mathbf{Z} = \mathbf{d} \cup \mathbf{X}$ (variates) $\cup\ \mathbf{z}^{LC}$ (load effects).
	(2b) RBDO MODULES
π	= reliability/robustness modules; subset of AM containing modules based on fn's **rx** (= n_p-tuple of probabilistically based **c** functions, e.g.: rx ≡ REL: $\mathbf{g}(\mathbf{Z}) \rightarrow \mathbf{p}_{fail}$; (set of failure probabilities/freqs **λ** of unwanted event e); rx ≡ROB: $a_i(\mathbf{Z}) \rightarrow$ robustness measure (e.g.Taguch's SNR); rx≡RISK: ($\mathbf{g}(\mathbf{Z})^T * \mathbf{CF}(\mathbf{Z})) \rightarrow p_{fail} *$ cf (e.g. risk of losing a ship). Output: values of probability ($P_{failure}$), robustness measure, risk ($)
	(2c) ANALYTICAL MODULES (AM)
Ω	= design quality modules; subset of AM containing criteria functions/mappings a_i. Output: **y** (attribute values)
α	= adequacy modules; subset of modules in the analysis model (AM) containing safety constraint functions/mappings g_i>0 (e.g. class rules). Ouptut $\mathbf{I}_{gi}$(pass, fail), normalized **g**-values [-1,1].
ρ	= response modules; subset of AM, containing modules for FEM procedures r_i. Output: $\mathbf{z}^{LC}$ (load effects).
ε	= environment/economy modules (loads, costs, etc.); subset of modules in AM with data generators E: $\mathbf{d}^{\varepsilon} = \{\mathbf{d}^{pressuresLC}, \mathbf{d}^{accelerationsLC}, \mathbf{d}^{masses}, \mathbf{d}^{costs}\} = \mathrm{E}(\mathbf{LC}) \subseteq \mathbf{d}$
Φ	= structural (physical) modules; subset of modules / modelers in AM/SM; data generators F, e.g. NAPA, MG, INDAT: $\mathbf{d}^{\Phi} = \{\mathbf{d}^{topology}, \mathbf{d}^{geometry}, \mathbf{d}^{material}, \mathbf{d}^{scantlings}\} = \mathrm{F}(\mathbf{d}^0) \subseteq \mathbf{d}$; $\mathbf{d}^0 = \mathbf{d}^{PROTOTYPE}$

Table 4. Integration of Design Support System–DeSS (Prebeg et al., 2014).

ID	SHELL / MODULE	SHELL DESCRIPTION
A8 8	*Γ (Δ (Ω))*	Interactive shell (GUI) containing control of modules in embedded shells. Used for: A I : DP (re)definition via structural and load descriptors $\mathbf{d}^{\Phi}$and $\mathbf{d}^{\varepsilon}$ (see Table 3) A II: subjective design selection in metric space using PSD techniques and AHP, HAW, ELECTRE solvers, see Table 6b
B7	**Σ (Δ(Ω,α))**	Shell for MODM or MADM adaptive generation of non-dominated (Pareto) designs based on MOGA, MOPSO, ES, MOSLP solvers, see Table 3a
C6	***Σ(π(Ω,α))*** ***RBDO***	Shell for reliability criteria based adaptive generation of designs using FASTREL and CALREL solvers (Zanic et al. 2014, Piric et al 2012), see Table 3b
D *5*	**(Ω,α)** **π(Ω,α) RBD**	Shell for definition of objectives and adaptation of criteria status (objectives and constraints) for their evaluation using criteria libraries in MAESTRO and OCTOPUS solvers or CSR library in MAESTRO-XML solver, see Table 3c
E4	***α (ρ), Ω*** **Ξ (*α (ρ), Ω*) -** *surr.*	Set of programs for quality, feasibility calculation (direct or via surrogate solvers Ξ) using Class or IACS CSR modules in OCTOPUS EPAN, MAESTRO ULSAP, ALPS/HULL, LUSA
F3	***ρ (Φ, ε)*** **Ξ (ρ (Φ, ε) -** surr.	Shell for calculation (direct or via surrogate solvers) of response fields (stresses, displacements) using MAESTRO, OCTOPUS and NASTRAN solvers, see Table 3c
G_2	***ε (Φ)***	Shell for definition/ input of design loads in TD and FD (ships RAO) and mission profile using solvers HYDROSTAR or MAESTRO WAVE, see Table 3c
H1	**Φ** (innovat, exper., prototype)	Shell (environment) for structural modeling using data generators MAESTRO, NAPA STEEL, FEMAP, USCS Ship Explorer, see Table 3c
A	*Back to A II*	Problem redefinition, MCDM decision making in PSD procedure

The resulting design support systems (DeSS) include objective (optimization solver) and subjective DM tools as parts of an iterative and interactive design process. They will endow the stakeholders with direct involvement in the design process and will support their educated decisions by sophisticated techniques for subjective decision making. The mathematical model for design synthesis, as used in DeSS, is usually formulated using Multi-criteria Decision Making (MCDM) techniques. They are divided into two basic groups: Multi-Attribute DM (MADM) and Multi-Objective DM (MODM). MADM is based on the selection among generated and evaluated designs that are based on a-posteriori defined preferences, while MODM generates designs for the selected set of designers' preferences using optimization techniques.

The structure of DeSS, given in Table 4, can be presented as a cascade of embedded shells (with IDs A-H in the 'babushka' style) of mathematical models or IT modules (direct and surrogate, see Section 4.6) for design analysis and synthesis (see Table 3). For integration tradeoffs, see also Section 4.3.

In the first row of Table 4 (denoted A or 8), the symbol **Γ (Δ (Ω))** denotes that interactive shell **Γ** contains controls of design definition shell **Δ** used to define criteria functions **c** via module **Ω**. It is design synthesis approach. AM are often integrated using inverse approach (in order, numbered 1→5 in Column 1 of Table 4). SM is mostly integrated in the A→C direction for control of running AM. For example, papers (Zanic et al., 2010, Prebeg, 2014 #297) present the structural DeSS rationale for the reliability based design optimization (RBDO) in the concept design phase (CDP), a phase when the most far-reaching decisions are made, regarding the attributes measuring the ship's safety and costs. These papers also demonstrate that using novel reliability based design (RBD) technique, the Pareto supported decision-making (PSD), with safety as one of the objectives, can replace the old paradigm where safety is only a constraint and thus promote a socially responsible design approach

While the concepts presented here are meant as a generic description of coupling of optimization and decision support, the DeSS system described has been directly implemented in the MAESTRO/OCTOPUS software. The initial DeSS system presented in Table 4 and the first row of Table 5 is based on the parallel processing-based RBDO procedure (Zanic et al., 1993) called OCTOPUS-Legacy. The new RBDO version is capable of working in the MAESTRO/OCTOPUS design environment (Prebeg et al., 2012) by using the very fast reliability calculation module FASTREL (Piric et al., 2013). Examples of the practical integration styles for modules and shells for MAESTRO and OCTOPUS DeSS are presented in Table 5 along with test models and recent references. Regarding novel MAESTRO optimization modules Σ and applications have also been described in recent conference papers: Ma et al. (2013b), Ma et al. (2014a), Hughes et al. (2014), Freimuth and Ma (2014), and Ma et al. (2013a), as well as a novel, very efficient loading utility described in a paper by Ma et al. (2014b).

Table 5. Integration of MAESTRO/OCTOPUS modules into DeSS.

Software / Test-model / (Reference)	Shell level Integration IDs	**Γ Δ** A or 8	**Σ** B or 7	**π** C or 6	**Ω** D or 5	α^{SP}/α^{US} E or 4	**ρ** F or 3	**ε** G or 2	**Φ** H or 1
(1) OCTOPUS-Legacy SWATH Patria (Zanic et al, IOS 1993)	A → H RBDO Parallel proc. 40 processors.	DeView ver.1	ES-AMC $X^{PC\,k} \subset X^{\geq}$	FOR M	MADM	Faulkner NLN FEM	2D FEM	SEA KEEPING FD	INDAT
(2) OCTOPUS DeMak Test BOX / SSC-398 (Zanic et al, OMAE 2014)	A → H RBDO DRM-SIMULATOR	DeView	MOSLP	DRM	MODM	SSC-398	ANALIT	INDAT	INDAT
(3) MAESTRO-Legacy LNG /EU FP6 MPROVE (Zanic et al, JEME2013)	1 → 7	OPTDAT	SLIP2	-	MIN WGT	Hughes	3D FEM	MG	MG
(4) MAESTRO/OCTOPUS RRM open ship (Zanic et al, PRADS 2013)	OCTOPUS A→ E[1] MAESTRO 1→ 4[2]	DeView	SLP/FD	-	MIN WGT	Hughes[2] Deflection[1]	3D FEM	MG	MG
(5) MAESTRO/OCTOPUS IACS CSR BC (Zanic et al, IMAM, 2015)	OCTOPUS A → E MAESTRO 1 → 3	DeView	SLP/FD	-	MIN WGT	CSR -ADEQ LUSA	MULTI-MODEL 3x3HOL D 3DFEM	CSR LOADS	MG

4.2 Parallel processing and hardware developments

The time span covered by this committee's report has seen rapid progress in both computational hardware for optimization problems and the usage of such resources for structural problems. Historically, computational hardware advances have been focused on allowing a new generation of modeling codes to become tractable. Any benefit for optimization has tended to be a secondary concern. Additionally, within the marine technical community, hydrodynamic simulation has typically been viewed as requiring high-performance computing (HPC) resources, while structural design has not. For example, in a recent review, McNatt et al. (2013) only associate HPC resources with the loads side of the structural design and optimization loop but not the structural response. However, HPC resources are beginning to appear in structural optimization literature. Experience of the members of the IV.2 committee indicates that 1,000 to 2,000 CPU hour structural optimization runs are easily within reach of most researchers using HPCs to parallelize out over tens or hundreds of cores. Such resources do result in the ability to tackle harder and more complex problems such as trade-space definition. To date, most work in this domain has focused on steps B-G defined in Table 4 above.

Cluster-style HPC resources still dominate the HPC literature to date. The long-term growth and dramatic reduction of cost of cluster-style computers, where hundreds or thousands of standard off-the-shelf CPUs are aggregated together have resulted in many opportunities for parallelization. Access to such machines is now commonplace at any major research university. As of 2014, the University of Michigan cluster “Flux” provides approximately 16,000 CPU cores for on-campus researchers. Similarly, the N8 cluster available to the University of Newcastle Upon Tyne has approximately 5,300 CPU cores, and the University of Zagreb has the 800-core cluster “Isabella” in-house. Typical optimization jobs can span tens or hundreds of these cores. Most clusters are configured with a Linux-based operating system and a variety of proprietary compilers and high-performance mathematics libraries. Linking the cores together is typically done through high-speed networking, with both custom-design protocols like Infiniband and more standard protocol, such as Gigabit Ethernet, implemented. Fully taking advantage of such resources typically requires manually modifying the code of each application to include multiple threads via threading libraries, such as MPI, and then compiling and linking with the system compilers and libraries. Thus, this approach is difficult to implement for closed-source applications unless the vendor can provide binary-level compatibility. Additionally, applications that have evolved around graphical user interfaces must be modified to run in a command or batch environment, as most HPC resources do not provide any display forwarding from the compute cores.

The growth of heuristic optimization algorithms, such as genetic algorithms or particle swarm algorithms, in which a population of candidate points needs to be evaluated frequently, is perfectly matched towards this type of cluster. Because each individual to be evaluated from the population is typically independent of all other individuals, this type of problem parallelizes very easily across multiple CPU cores. There is typically minimal need to communicate among individuals during evaluation, so data sharing and transfer speeds tend to be less critical, although data must be able to flow back to the master optimization process quickly. In practice, such optimization approaches have proven practical, using hundreds of cores joined only via standard gigabit networking. Another advantage of this approach is that the MPI and thread code can be confined to the optimizer with the objective function relatively untouched. In fact, if the per-call time of the objective function is long enough, it is possible to use operating system-based file writing to move data in and out, greatly reducing the need for efficient parallel threading in the codebase. This also allows existing, closed-source applications (e.g. ANSYS, Abaqus) to interact efficiently with an optimizer over tens or hundreds of cores, provided sufficient software licenses exist to run the required instances of these codes.

A more recent development has been the introduction of computation on graphical processing units (GPUs). Driven by the need to provide renderings for computer games and other 3-D applications, graphics cards now feature anywhere from tens to thousands of limited, calculation-focused computational cores. By running computationally-intensive code on these cores, instead of on the main CPU, it is possible to further accelerate many calculations. As most graphics cards are small, it is possible to have a “mini-cluster” on each user’s desktop. Additionally, such functionality can be accessed via conventional GUI-type applications and development environments like MATLAB and Maple which have been compiled with GPU support. The downside to GPU processing is that custom code is needed to access and run on the GPU themselves, much like (but incompatible with) the MPI code needed for cluster computing. Thus, programs typically need to be re-written, not just re-compiled, to work with GPUs. While this re-writing can focus only on the performance-critical areas of the code, this still represents a time-consuming undertaking and requires full access to the relevant source code. An alternative approach proposed by Prebeg et al. (2014) is to use surrogate models, built in a GPU-aware framework to stand in for optimization components that it would be inefficient to re-compile. However, simulations that are needed to build up the surrogate models must still be executed outside of the GPU, or even in a parallel computing setup if the original applications are not compatible with the available parallel computing hardware.

Cloud computing has also emerged during the last three years as a significant approach for managing optimization and high-performance computing resources. In the cloud approach, the vendor bundles the software and necessary licenses, computational hardware, and data storage into a single package that can be rented or leased to the designer. For example, Altair's Hyperworks and the related topology optimization can be run remotely on Altair's servers, or Altair will build a custom hardware and software package that can be physically installed in a client's office. This abstraction of much of the details of applying high-performance computing to design allows design offices to treat high-performance computing as sort of utility cost that can be scaled up or down as business demands. Additionally, end designers can access the increase computational power through similar GUI-driven applications they are used to using. While it frees the business from the overhead of developing, running, and training staff on a bespoke HPC solution, most cloud solutions are standardized and lack the full flexibility of a bespoke solution.

It is evident that high-performance parallel computing infrastructure has become easily available, not just to research institutions but even to small design offices. Even more, cloud computing enables usage of those resources "on demand," which significantly reduces overall computing cost to users that do not have constant requirements for HPC computing. However, it seems that those capabilities are not adequately utilized in the ship structural design community and that the main reason for this is a low level of adoption of ship structural design software to parallel execution on currently available high performance parallel computing platforms. The reason for this is most likely due to the fact that in the small ship structure community, ship structural design tools are developed by ship structural analysis and design experts, not by numerical mathematicians or computer science experts (e.g. MAESTRO, LBR5). At the same time some general purpose structural analysis tools (e.g. Abaqus) are well adopted for almost all HPC platforms, but those tools are not widely used in the ship structures community, especially not for purpose of dimensioning the structural components according to classification society rules (e.g. Stage 2 models in IACS CSR for Bulkers and Tankers). Another possible reason is that the actual performances of those tools were good enough for applications on real life structures, even in early 1980 (Hughes, 1988). Thus, the identification of a necessity of a code adoption to parallel computing came fairly late. Currently, this need is primarily driven by the desire to be able to generate a Pareto frontier for the entire global ship structural design, not just for substructures. Additionally, the ability to include reliability-base calculation (e.g. structural safety) in the constraints or objectives of this global problem is desired. Constraints, or even objectives, include reliability-based calculation (e.g. structural safety). Therefore, one of the largest challenges in the following period is to adopt the tailor-made ship structural analysis and design software for parallel execution on currently available high performance parallel computing platforms.

4.3 Developments in structural optimization algorithms (optimization solvers-Σ)

Currently, manufacturers of ships and offshore structures are operating under difficult conditions. Facing strong competition, they are forced to meet the expectations of their demanding customers. Such circumstances require ship and offshore structure construction enterprises to focus on assuring quality, satisfying their customers' wishes, and continuously improving of their businesses. The ability to design and manufacture high quality structures–built as various one-off items or in short series–while simultaneously fulfilling the economic manufacture requirements are factors that determine whether the enterprise will survive in the market, hold its market position, and keep developing.

Given the above, it is normally impossible to assess variants of proposed solutions using a single criterion (which allows for a very clear interpretation, such as the cost, and is sufficiently, accurately definable in early design stages). Therefore, the conditions under which the decision is to be taken can be improved by entering multiple criteria into the decision-making model. This initially entails the need to design and manufacture structures characterized by *cost-effective exploitation* as well as *cost-effective construction*, or simply the need for ship or offshore structure optimization in respect of cost-effective exploitation and cost-effective construction. More and more attention is given to the requirement of cost-effective and environment-friendly utilization of such structures after their lifecycle has ended, namely *cost-effective utilization*. Therefore, both in the design stage and during the manufacture, the most advantageous decisions possible that guarantee goal attainment are expected. One of the main measures allowing for such goals to be attained is optimization. Favorable conditions for this have been provided by the development of ship and offshore structure optimization methods and techniques that have been observed for many years. Unfortunately, the progress in their practical utilization has been much slower. Many of them were discussed during previous congresses. Because structure optimization is mainly concerned with complex computational procedures, in order for such optimization to be run, it is necessary to formulate suitable mathematical models for the structures subjected to optimization and to apply algorithms that are effective in solving defined problems and that render solutions at acceptable costs, namely *cost-effective optimization*.

In most cases the multi-objective optimization problems in ship and offshore structures design are solved in two steps:

(1) Determining a set of compromises/trade-offs (Pareto optimum),
(2) Selection of the preferred solutions/variants/candidates from the set of compromises. Such an approach corresponds with the Pareto Supported Decision-Making (PSD) strategy discussed in the introduction to this chapter.

To date, mainly deterministic assessment criteria have been used for the purposes of determining the set of compromises. All such criteria are treated as equally important and taken into account together with subjectively determined weighting factors representing value differences among such criteria for the decision maker. When choosing the best solution, or the most preferred compromise in the set of compromises, selection is done with the use of an additional (typically new) criterion. In papers published within the time-frame concerned (since 2011), their authors present a single set of compromises, a set of non-dominated solutions that constitutes a solution of the multi-objective optimization problem they formulated. In their works, they do not discuss the issues of selecting the preferred compromise or set of compromise solutions in the set of non-dominated solutions. Neither do they discuss the quality of the set of non-dominated solutions obtained. However, it is known that when applying optimization algorithms using random solution generation procedures (e.g. genetic algorithms) and/or random procedures for selecting generated solutions for subsequent iterations (e.g. genetic algorithms, simulated annealing), different sets of non-dominated solutions are obtained when any change is made to the variables controlling the course of the optimization calculations. In such cases, one should therefore produce more than single set of compromises and then all the sets should be analyzed and evaluated using statistical methods as well. The rationale for the production of a single set of compromises can be high cost and long calculation times as well as high complexity of the optimization object which are ships and off-shore structures. In most cases may be satisfactory to obtain one set of compromises only; however the lack of rigorous convergence criteria for this class of optimizers represents a continued challenge.

Since 2011, no definitively new approach has been proposed to formulating and/or solving ship and offshore structure optimization problems. Existing computational algorithms and computer codes have been developed. Computational procedures have been expanded and tested in subsequent cases. The authors have improved the existing algorithms to increase the effectiveness of the computational procedures and/or to build user-friendly computing environments (e.g. a graphical user interface). The existing development environments (e.g. LBR-5, OCTOPUS) are being improved, or new ones are being built, which integrate numerous computational tools including ones for structure optimization and analysis for the purposes of assessing the limitations formulated. The results of reach and application works are presented and reviewed in condensate form in Table 6.

Table 6. Summary of research and application of optimization for ships and offshore structures.

Authors	Optimization Method	Problem solved, main results and comments
Deterministic algorithms for single-objective optimization (1 publication)		
Bayatfar et al. (2013)	SIMPLEX method	The single-objective optimization of deck structure.
Deterministic algorithms multi-objective optimization (1 publication)		
Motta et al. (2011)	Convex linearization and a dual approach	The hull structures of a 60-m mega yacht multi-objective optimization regarding the cost and weight of the structure. They showed that the optimization analysis application in the preliminary design stage leads us to important gains in terms of cost and weight with respect to the initial scantlings. The advantages of a structural optimization are particularly useful if they can be applied during the first stages of the project.
Randomized (e.g. evolutionary etc.) algorithms for single-objective optimization (4 publications)		
Devine and Collette (2013)	Single-objective genetic algorithms (GA) and the Bayesian optimization algorithm (BOA)	A single-objective optimization T-Craft midship section with respect to production cost. A single-objective optimization was conducted to minimize production cost while maintaining sufficient longitudinal strength requirements as recommended by the Guide to High Speed Craft as set by the American Bureau of Shipping.
Kawamura et al. (2013)	Single-objective genetic algorithm (GA)	The midship section of a double hull tanker VLCC structural optimization with respect to construction cost and Life Cycle Benefit (LCB). The authors present results of lifecycle structural optimization of the midship section of a

Authors	Optimization Method	Problem solved, main results and comments
		double hull tanker considering multiple risks about not only the risk of failure but also the environmental risks and the economic risks.
Kitamura et al. (2011b)	Genetic algorithm (GA)	The weight minimal optimization problem of the bottom structure of a bulk carrier.
Sun and Wang (2012)	Support vector machine (SVM) and genetic algorithms (GA)	A statistical learning theory applied in SVM was proposed, which specializes in studying the situation with a small number of samples. This theory could help to solve the structure selection problem and local minimum problem existing in traditional learning machines. As an example, they presented the optimization of the midship of a very large crude carrier (VLCC) ship according to the direct strength assessment method in common structural rules (CSR) with respect to structural mass. In this paper, a hybrid process of modeling and optimization, which integrates a SVM and GA, was introduced to reduce the high time cost in structural optimization of ships.
Randomized (e.g. evolutionary etc.) algorithms for multi-objective optimization (10 publications)		
Cui et al. (2012)	Multi-objective particle swarm optimization and the multi-objective genetic algorithm NSGAII (Non-Dominated Sorting Genetic Algorithm-II)	The multi-objective optimization of a bulk carrier structure with respect to weight of the structural materials and cumulative fatigue damage. The results obtained indicate a possibility to make weight savings compared to the original design. The fatigue indexes were also reduced, which means the structure can last longer under the same operational conditions.
Cui and Wang (2013)	Multi-Island Genetic Algorithm (MIGA)	Optimization of a container ship cargo tank's midship section with respect to weight of structure. They presented an application of knowledge-based engineering in container ship cargo tank structural design and optimization. Ship design is such a complicated multi-discipline task that knowledge-based engineering can assist in design and optimization. In this design process for new ship structures, the relevant knowledge is automatically distracted from knowledge base and executed together with the knowledge reasoning technique.
Ehlers and Kujala (2013)	Particle Swarm Optimization (PSO) algorithm	The optimization of stiffened panel from a case study vessel with respect to lowest cost per mass (C/M) ratio, which reduces both cost and mass [(C+M)/(C/M))]. A PSO algorithm, coupled to nonlinear FE-simulations and a production cost assessment, was utilized in order to optimize the design alternatives in compliance with the uniform and non-uniform ice loading.
Fu et al. (2012)	Adaptive Simulated Annealing (ASA)	A multi-objective optimization of a container ship structure considering a tee-stiffened plate structure with respect to structural mass in the static analysis and maximum acceleration of structure in the dynamic analysis. A new improved collaborative optimization (CO) model, one of multidisciplinary design optimization (MDO), is used.
Ji and Wang (2013)	Multi-Island Genetic Algorithm (MIGA)	A multi-objective optimization for the ultimate strength of a ship hull in multiple load cases.
Pedersen et al. (2015)	Particle Swarm Optimization (PSO) algorithm	Identify the conceptual design alternatives for ice-classed vessels. The midship structural arrangement of an LNG tanker and of a general cargo ship were optimized with respect to structural weight and cost (M, C/M).
Sekulski (2011a, 2011b, 2011c, 2013, 2014, 2015)	Multi-objective genetic algorithm (GA) with combined fitness function	The multi-objective optimization of the hull structure of a passenger and vehicle ferry. Figure 3 shows condensed data for calculations and the results obtained: a set of solutions for the assessments of which are non-dominated in a Pareto sense.
Sobey et al. (2013)	Genetic algorithm (GA)	The composite boat hulls optimization with respect to structural mass and cost. This paper examines the way in which rapid assessment of stiffened boat structures (composite structure) can be performed for the concept

Authors	Optimization Method	Problem solved, main results and comments
		design stage.
Temple and Collette (2013a)	Multi-objective genetic algorithm NSGAII (Non-Dominated Sorting Genetic Algorithm-II)	The multi-objective optimization of a naval vessel structure with respect to structural weight and lifecycle maintenance costs. Fatigue and corrosion damage over the course of its service life are taken into consideration.
Vasconcellos et al. (2015)	Genetic algorithms (GAs)	The midship section design of a double-hull tanker optimization with respect to power, deck wetness, slamming, steel weight, and structural safety. Mode Frontier software was used to integrate the mathematical model and find the best solution.

As it appears from the review, the majority of the works are concerned with the use of randomized algorithms to single- and multi-objective optimization. Only two teams reported results related to a deterministic single-objective optimization. In all papers concerned with a randomized single-objective optimization, genetic algorithms were used. As it comes to works focusing on multi-objective optimization, most authors report the use of genetic algorithms. Two teams reported that they had used a particle swarm optimization algorithm. One team reported that they had used a simulated annealing algorithm.

There are additional works related to the development of the frameworks for ship structural optimization and analysis. Frangopol et al. (2011) presented a general framework for the probabilistic analysis of ship structures in terms of reliability, redundancy, fatigue, material deterioration, damage detection, monitoring, and inspection optimization. Kitamura et al. (2011a) presented a structural optimization system using the Finite Element Method (FEM) for the initial design stage of a ship. A general bulk carrier was selected as the object for the optimization. A numerical example showed that the proposed method makes it possible to optimize the shape of the ship's bottom structure. McNatt et al. (2013) used MAESTRO, a practical CAE tool for ship structural design and optimization. The achievement of improved performance, including several aspects related to improved performance of the ship's structure, is fundamental to the evolution of ship classes and size for different types of cargo and service. Examples of structural performance contribution to overall ship engineering and economic performance include the following:

- Higher performance structures in terms of reduced weight with higher degrees of safety and reliability
- Lower fabrication costs
- Better economic performance in terms of lower contribution to lightship weight and hence, larger payload fractions
- Reduced structural maintenance costs over the lifecycle
- Recognition of social responsibility in terms of environmental protection, collision/damage tolerance, reduced risk of failure, etc.

Recent decades have also seen increasing pressure by ship owners and operators for ships that deliver high returns on investment. Zanic (2013) presented the application of the OCTOPUS DeView 5D (OCTOPUSDesigner 2012) system to the optimization of the ship's structure in respect to its weight. The basic concepts and methods for multi-criteria synthesis of complex thin-walled ship structures in concept and preliminary design are presented. Multi-criteria decision making (MCDM) techniques are used. They are divided into two basic groups, multi-attribute decision making (MADM) and multi-objective decision making (MODM). MADM is based on the selection among generated and evaluated designs from a posteriori defined preferences, while MODM is based on optimization techniques to generate designs for a selected set of designers' preferences. Zanic et al. (2013a) presented the application of the MAESTRO/OCTOPUS design support system to the multi-objective optimization of a Ro-Pax ship structure. They used several optimization algorithms: Monte Carlo sampling, sequential adaptive generation, multi-objective genetic algorithms (MOGA), evolution strategies, simulated annealing, and multi-objective particle swarm optimization. The design support methodology (i.e. techniques and procedures) for multi-criteria synthesis of large thin-walled ship structures in concept and preliminary design is presented. Papanikolaou et al. (2011) describe the essential features of a modern, integrated approach to ship design, such an integrated design software platform, and demonstrate its implementation in practice: multi-objective optimization of oil tanker hull structure in reference of Freight Rates (RFR), Oil Outflow Index (OOI), Energy Efficiency Design Index (EEDI) and maximum speed for given main engine margins as integrated design and multi-objective optimization.

Yang and Wang (2012) proposed a methodology for fatigue reliability-based design optimization (RBDO) for the design of a bending stiffener. RBDO is more meaningful, which is concerned with the probabilistic constraints evaluated through the reliability analysis.

There are various criteria that can be used for assessment of the effects of optimization in designing ship and offshore structures. An optimally-shaped structure can be compared to a design made by an experienced designer. However, certain difficulties are to be expected here. Thus, for certain typical simple structures, the optimization effects amount to a few percentage points, whereas for more complex and untypical structures, such effects may amount to a dozen or so percent.

Because running an optimization process would extend the design stage's duration and increase its cost, the conclusion is that optimization is only meaningful in the case of manufacturing series of structures or their elements in which even a slight percentage unit profit will yield large-scale global savings and in the case of untypical costly structures, for which substantial unit savings will thus be secured.

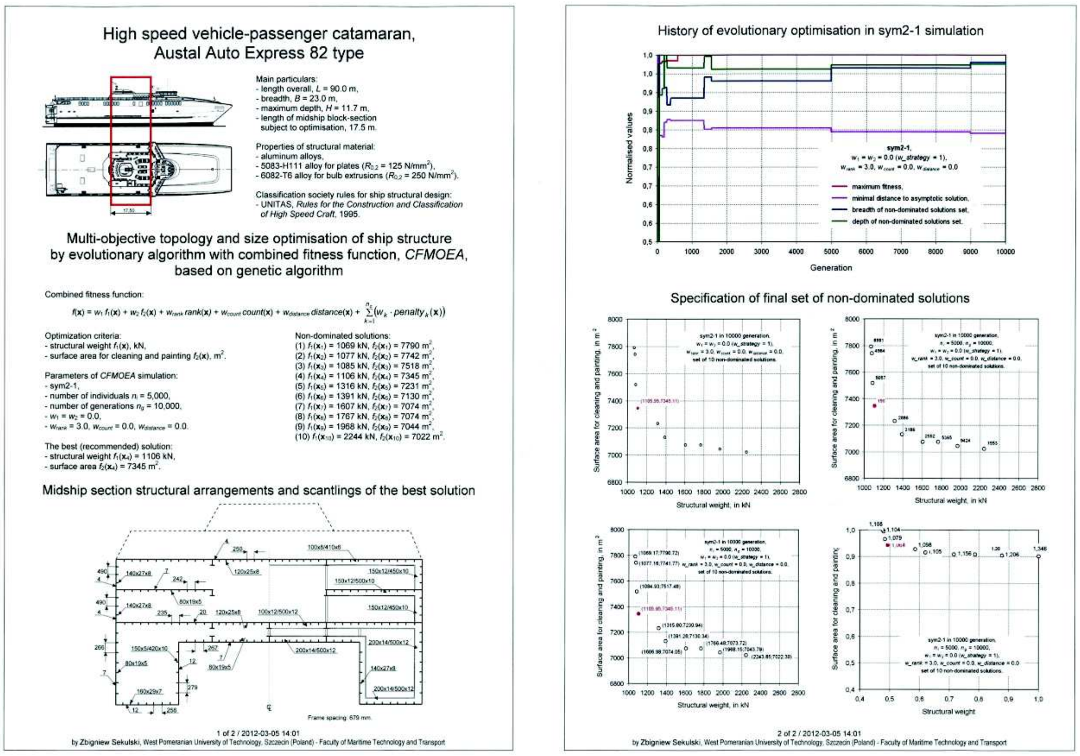

Figure 3. Data and results of evolutionary multi-objective optimization of ship hull structure (Sekulski, 2012).

There are various randomized multi-objective optimization methods reported in this section among which multi-objective evolutionary algorithms have received significant attention (7 publications). These techniques usually generate a finite set of solutions to approximate the Pareto frontier of a multi-objective optimization problem (e.g. Fig. 3). However, obtaining the 'best possible' set to represent the entire Pareto frontier is not always a trivial (or even an objectively-defined) task. From these reason performance assessment and comparison study of such techniques should gained much attention. One obvious way to compare the algorithms is to simply visualize the final sets of solutions and rely on intuitive judgments to decide on superiority of one technique to another. However intuitive and visual assessment is not a reliable tool for comparison of different multi-objective optimization techniques. Because of that a theoretical as well as practical developments regarding to a performance metrics that can be used for a comparison study of different algorithms is needed. These performance metrics generally should be capable to assign an absolute or relative value to determine whether it is a 'good' performance of the algorithm. These metrics should be useful for the effective and quantitative measure all desired aspects of quality in compromise solution sets obtained by different algorithms as well as performance of optimization algorithms without redundancy. Proposed metrics should allow for helps the decision-maker a quantitative and objective comparison of the performance of the different multi-objective optimization algorithms applied/developed for ship and offshore structures.

4.4 Surrogate modeling and variable fidelity approaches (surrogate solvers–Ξ)

Surrogate modeling refers to the replacement of a computationally-intensive prediction model with a simpler surrogate, typically built from strategic samples taken from the computationally-intensive model. The methodology of surrogate (also referred to as approximation or metamodeling) modeling evolved from classical Design of Experiments (DoE) techniques for conducting expensive physical experiments into Design and Analysis of Computer Experiments (DACE). The main and particularly important differences between the methodologies are the nonexistence of random errors for deterministic computer experiments and the adequacy of the models, which is determined by systematic bias.

The surrogate modeling (metamodeling) and its role in support of engineering design optimization is illustrated in Figure 4.

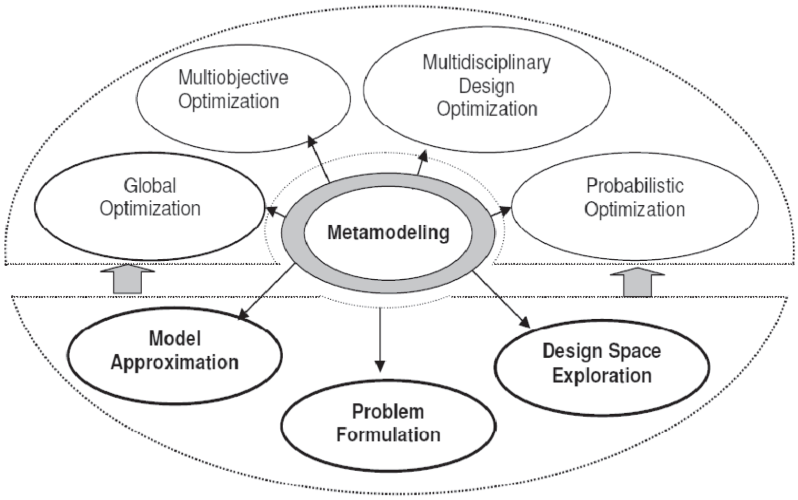

Figure 4. The role of metamodeling in support the engineering design optimization (Wang and Shan, 2006).

A recent survey (Viana et al., 2014) of more than 200 scientific papers examines application of surrogate modelling in aerospace engineering multidisciplinary optimization community in the past 25 years. The authors opinion is that the 'curse of dimensionality' still exists as problems have just gotten larger and that new metamodeling techniques are needed to handle the peculiarities of high-dimensional problems. They believe that global sensitivity analysis will play an important role in alleviating the curse of dimensionality, and many are investigating approaches to reduce the computational expense associated with high-dimensional problems. In addition they specify problems with computational complexity, numerical noise and challenges of handling mixed discrete/continuous variables. The validation of metamodels and the underlying model is as critical as before. A related wide open field for research is the incorporation of the error of the metamodel and the underlying model itself into the problem formulation.

One of the conclusions of ISSC2012 concerning the surrogate modeling was that the "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…" (2012). In 2015, there are many reported results from comparative studies of several metamodeling techniques, which are applicable for different engineering fields. The metrics used in this comparison are as follows:

- Accuracy: the capability of predicting the system response over the design space of interest
- Robustness: the capability of achieving higher accuracy for different problem types and sample sizes
- Efficiency: the computational effort required for constructing the surrogate model and for predicting the response for a set of new points by surrogate models
- Transparency: the capability of illustrating explicit relationships between input variables and responses
- Conceptual simplicity: the ease of implementation

The common opinion according to Prebeg et al. (2014) from the different tests problems with low or high level of nonlinearity and small (2, 3) or large (>10) number of input variables concerning the accuracy of accepted modeling techniques is summarized in Table 7. Three of the most popular modeling techniques are response surface (RS), Kriging (KG), and radial basis functions (RBF). The accuracy of every model must be validated by comparing the model and underlying prediction method on samples distinct from those used for fitting the model.

Table 7. Preferred techniques for different problems concerning accuracy.

Nonlinearity	Number of input variables	
	Small	Big
Low	RS	KG
High	RBF	RBF

The survey of the reports from last three years points out two main directions in development of the surrogate modeling: automatic design and optimization, and risk and safety analysis.

4.4.1 Surrogate modeling in design and optimization

The main objective of the research of Prebeg et al. (2014) is to improve the design process of complex thin-walled ship structures through an application of surrogate modeling. The methods considered are integrated into an interactive computing environment for multi-criteria design in order to enable effective and efficient interaction between the designer and the design problem within a given design timeframe. Surrogate modeling was applied to the approximation of structural responses in order to reduce the number of FEM calculations inside of the optimization loop. Applicability of the proposed approach and suitability of different surrogate modeling methods is extensively tested on a simple barge example.

The cost of surrogate modeling is influenced by the number of control factors and the number of computer experiments (i.e. simulations) using FEM. One possible solution to reduce the total number of control factors is to treat beam descriptors (height and thickness of web and breath and thickness of flange) as one composite descriptor using its e.g. moment of inertia or section modulus as a control value. In this way, it is possible to reduce the number of control factors in the barge example from 35 to 11, eight of which are beam composite control factors.

Another important factor that influences the computational complexity of the structural response surrogate approach is the number of surrogate models that must be created. For example, in the case of the RoPax ship design, about 7000 surrogate models for each load case are necessary. One possible reduction is to create a surrogate model of the mean value of certain structural response (e.g. σ_x) on all adequacy elements (patches) in some substructure.

Due to the complexity of the design process in the real, practical applications, and in order to enable a flexible execution, the DeMak–OCTOPUS Designer environment is used. An important property of the proposed design sequences is the possibility of parallelization which can take advantage of today's multi-core and multi-processor workstations.

A hybrid between the well-established strength Pareto evolutionary algorithm (SPEA2) and some commonly used surrogate models is presented by Kunakote and Bureerat (2013). Several surrogate models, including quadratic function, radial basis function, neural network, and Kriging models, are employed in combination with SPEA2 using real codes. The various hybrid optimization strategies are implemented on eight simultaneous shape and sizing design problems of structures, and they take into account the structural weight, lateral bucking, natural frequency, and stress. Structural analysis is carried out by using a FEA. For a design problem with mass and natural frequency as objective functions and stress and buckling as constraints, SPEA using RBF is the best method. Nevertheless, for all considered design problems, the overall top performer is SPEA2 using the quadratic regression; SPEA2 using the Kriging model is a close second-best.

Surrogate models are used by Chen et al. (2013a) for reliability-based robust design. The proposed Surrogate Based Particle Swarm Optimization (SBPSO) algorithm combines the surrogate modeling technique and particle swarm optimization. The algorithm and its efficiency are displayed through numerical examples of a composite pressure vessel comprised of an aluminium liner and T-300/Epoxy composites. The responses are analysed by using FEM (performed by ANSYS software). An optimization problem for maximizing the performance factor is formulated by choosing the winding orientation of the helical plies in the cylindrical portion, the thickness of metal liner, and the drop off region size as the design variables. Numerical examples show that the optimal results of the proposed model can satisfy certain reliability requirements and are robustness to fluctuations of the design variables.

An automated optimization procedure based on successive response surface method is presented by Pajunen and Heinonen (2013). The approach is applied to the weight optimization of a stiffened plate used in marine structures. In the design space, the surrogate model is spanned sequentially into an optimally restricted subspace that converges towards at least a local optimum. Both the objective function and all constraint functions are modeled using the linear response surface method, enabling the use of a robust and efficient simplex algorithm for the optimizations. The approach links SolidWorks and ANSYS software, and optimization is made in a MATLAB environment. Being a practical optimization problem, to generate a discrete variable optimum solution from the continuous problem solution, a simple binary integer optimization is adopted. The binary integer optimization problem is solved using the branch-and-bound method.

4.4.2 Surrogate modeling in risk and safety analyses

Polynomial Chaos Expansion (PCE) is a special kind of response surface for random variables by which the stochastic properties of the responses can be easily obtained by using the orthogonal properties of the polynomial. This kind of response is used by Htun and Kawamura (2013) to study the stochastic properties of the ultimate tensile. First, the hypothetical corroded surfaces, which represent the thickness reduction of corrosion, are generated by a random field model (Karhunen-Loeve Expansion Method). Second, the random characteristics of the minimum cross sectional area of the generated plates with random field corrosion are estimated by PCE method as well as Monte Carlo simulation to evaluate the availability of PCE to estimate stochastic properties of strength of the corroded plate. By using PCE, the number of samples can be reduced significantly to get the most accurate results for time consuming analysis. Third, the ultimate tensile strength of the plates with random field of corrosion is obtained by non-linear three dimensional FEA. Based on FEA results, stochastic properties of the ultimate tensile strength of the plates with random field corrosion are obtained.

The surrogate modeling penetrates the rapidly growing industry of offshore wind turbines. Taflanidis et al. (2013) discussed the quantification and evaluation of risk and development of automated risk assessment tools, focusing on applications to offshore wind turbines under extreme environmental conditions. The framework is based on a probabilistic characterization of the uncertainty in the models for the excitation, the turbine, and its performance. Risk is then quantified as the expected value of some risk consequence measure over the probability distributions considered for the uncertain model parameters. Stochastic simulation is proposed for the risk assessment, corresponding to the evaluation of some associated probabilistic integral quantifying risk, as it allows for the adoption of comprehensive computational models for describing the dynamic turbine behavior. For improvement of the computational efficiency, a surrogate modeling approach is introduced based on moving least squares response surface approximations. The framework for risk quantification and assessment was also extended to an efficient, sampling-based sensitivity analysis. Such analysis aims to identify which of the critical uncertain model parameters are contributing the most to overall risk. The efficiency of the surrogate model was further exploited to develop a standalone risk assessment tool that can facilitate an automated implementation of the proposed risk quantification and assessment framework.

The surrogate modeling is very often combined with Monte Carlo simulations. Such an approach is used by Georgiev (2011) for safety analyses of still water loads for bulk carriers. The goal was to study the influence of deviations from cargo loading plan on net load of double bottom and still water bending moments. For example, a Handymax BC-A type ship is used. The metamodels approximate the work of the installed, on-board, mandatory loading instrument and give the relation between the distribution of cargo and the trim and still water bending moments in controlled sections. The Monte Carlo simulation uses the fitted metamodels to obtain a rich set of statistical data that permit preparing event tree analysis for possible overloading of double bottom and the evaluation of likelihood for exceeding of permissible bending moments.

4.5 Optimization for production (design quality modules–$\Omega^{PRODUCTION}$)

An important subset of the overall optimization problem is that focused on optimization for production. For many commercial shipyards, minimizing the production cost of the vessel is critical to winning competitive contracts, and hence this topic has received extensive attention. The University of Wisconsin (UW) and the Marinette Marine Corporation (MMC) developed a shipyard orientation program course targeted to newcomers and non-shipbuilders in order to teach a basic understanding of shipyard layouts and functions through a 3-D virtual shipyard layout modeled on Navisworks Freedom. According to the University, the model represents various items seen in a shipyard and can even be customized to represent a specific yard. Through this development, UW became the first institution in North America to offer fast track, distance-delivered courses in a full certificate program in modern shipbuilding design that could provide an asset in effectively training production personnel Lundquist (2012).

Lodding et al. (2011) presented Virtual Reality (VR) as a tool to aid in the adherence of budgets and due dates in the shipbuilding industry by developing accurate planning and fast reactions to unplanned events such as late deliveries or assembly parts. In particular, their article addresses that there is no concept for an automatic session preparation according to new assembly and no software-based support for finding and verifying a new assembly sequence using VR. Thus, an assembly planning prototype was developed for collecting model data and dynamic meta data, which allows for fast and automatic model manipulation and planning information. This reduces time and the occurrence of errors during the preparation and execution session. A prototype of the VR model is currently under evaluation in cooperation with a German shipyard.

Production management based on simulations rejects decision-making based on experience and intuition and values the establishment of improvement methods based on quantitative and concrete data. Lee et al. (2014) applied a simulation using software tools, such as DELMIA, to the work plan as part of the production planning in shipyards in order to provide optimal decision-making through models reflecting virtual shipyard facilities and spaces. The simulation environment is based on discrete event simulation and is designed to enable the determination of production output, capacity, process flow congestion, bottleneck identification, and material requirements at the work-stage level.

Nienhuis (2012) initiated the development of an automatic sequence generation system, capable of generating the interference-free assembly sequences that identify the relationships among outfitting activities and estimate the reasonable mounting time. The system contains three fundamentally automated processes: assembly knowledge representation, data acquisition and preparation, and sequence generation. The goal of this model is to generate a reasonable assembly sequence of non-structural components in the outfitting processes, under the assumption that the various resources, such as drawings, material, and equipment, required to perform the activities are always available. The research only takes the geometrical aspects of components into account. The output of this research project is not the development of a scheduling tool that commits all kinds of resources among a variety of possible tasks, but the determination of the technical dependencies among different assembly tasks that helps to optimize both the planning and production processes. Thus, the onsite coordination and installation effort can be reduced, and the level of advance outfitting practices maybe increased, which leads to the reduction of cost and lead-time.

Dong et al. (2013) present a two stage queuing model for shipbuilding outfitting process. Their article tackles the problem of determining when the outfitting work for each block should be processed during ship construction. Stages of ship production are simplified into two with the first stage representing the general assembly process associated with block construction and the second stage representing the grand block construction. Therefore, a model is formulated as a queuing system to provide information on how to optimally distribute the outfitting work at each stage in the shipbuilding process. A closed formed equation for system cycle time is applied by using Kingman's equation from queuing theory and calculates the optimal percentage of total outfitting work processed at each stage can be calculated given any scenario.

Kajiwara (2013) tries to identify the important wastages in a shipyard that can increase production time and cost and to design the production system of a shipyard based on lean philosophy. Simulation modeling is used to evaluate the performance of the production system, and Kanban is a pull-type scheduling method that can be used to simulate the pull production system of a shipyard for the optimization analysis. The reduction of waiting times for various block assembly strategies are obtained, and as a result, the overflows of the sub-blocks and blocks in stockyards are notably reduced. Kanban is used as the supplementary tools that can contain the information of the products and production system, and it can help to pull the blocks in production lines and to maintain the amount of production.

Tokola et al. (2013) study the scheduling of block erection in shipbuilding and formulates a mathematical model to minimize the time between the start and finish of the erection schedule when different lifting and joining times are considered by taking structural stability and no-skipped-blocks as constraints. Although the mathematical model used is simplified and should be further examined by varying constraints, the solutions presented in the article give insight into how the design and production parameters generally affect the production time, which could be an important factor in the early design of the ship.

In the 10th International Conference on Computer and IT Applications in the Maritime Industries, Caprace (2011) presented a ship block erection process using discrete event production simulation and optimization. The purpose of this study is to examine how various computer-based analyses and simulation techniques can be used to improve the efficiency of the block sequence definition process, as the process is usually lengthy and subject to errors, leading to a non-optimal block sequence. The study also discusses the reasons why shipyards do not use simulation tools alongside the various advantages of simulation in terms of layout and production planning. The case study focused on the erection of a Suez Max tanker, which initially begins with selecting blocks one by one to be erected, and at each stage of the selection process, a list of potential neighbor blocks are provided, which satisfy the technical conditions in order to proceed with the block selection sequence process. The sequences are then entered into the DES software (QUEST) which evaluates the lead time of the production process. Once this is executed, optimization software (ModeFRONTIER) is applied to optimize lead time by modifying input variables and analyzing the outputs, which are defined as objective functions or constraints. Although the initial results of this study reached no convergences for reasons explained by the authors, it is important to highlight that the model generates only the feasible block sequences, thus avoiding non-feasible design processes, and the analysis concluded that the block erection rule by layer takes approximately 6% more time to complete compared to erection by slice or pyramidal propagation. Production simulation tools are useful regarding the possibilities of gains in the process of production and cost reduction.

4.6 Optimization for lifecycle costing (design quality modules–Ω^{LCC})

To effectively support future ship design, maintenance, and service-life extension decisions, Collette (2011) proposed that it is necessary to extend the existing semi empirical, component-based structural design rules based primarily on safety concerns for a system performance model for ship structures. This system-based approach extends the existing rule-based approach by formally stating performance requirements for the structure based on the vessel systems that the structure supports. By setting performance targets, it is possible to assign key performance parameters (KPP) and key system attributes (KSA) to the structural system, and to allow the overall vessel design synthesis work to evaluate different structural concepts and weight budgets against achieved vessel performance attributes. Potential difficulties in making this transition are discussed- such as combining structural tools capable of producing the required metrics with associated measures of uncertainty–that are critical for combining structural with other design metrics in an absolute frame such as cost effectiveness. Moreover, difficulties in following traditional system engineering partitioning and decomposition approaches with structural systems are observed.

Bharadwaj and Wintle (2011) present an innovative and a pragmatic application of risk-based principles for planning inspection to the ship hull structure. The approach described in this paper uses semi-quantitative measures (FMEA, RPN) and the ECI planning is informed by reports from CI and engineering judgment/expert opinion, as well as operating data from a relevant sample of ships from a generic database such as the one within the RISPECT project. This paper extends principles in asset integrity management and the risk model is separated into two parts. The first part is a technique for assigning priority to structures within the ship hull based on certain measures of risk. The second part is used for optimizing inspection actions, given the risk-based order of priority established in the first part. The application of this approach has the potential to reduce the operation and maintenance costs of ships and increase their reliability.

Moreover, the American Society of Naval Engineers published a research article (SNAME, 2011) aiming at identifying what actions can be taken to control LCC of a surface ship and developing a potential list of obstacles in the design, construction, testing, and in-service support. Total LCC is addressed by proposing actions such as reducing cost through weight constraints (cost estimates not accurate, operations and support costs not updated as design matures), manning, and automation (inadequate manpower evident from reduced readiness, deferred maintenance etc., deficiencies in hardware and software). The article also compares surface ships to the submarine community, which places considerable priority to maintainability, a major factor in altering the LCC.

Apostolidis et al. (2012) conducted an investigation of the relationship between dry-docking cost and its significant determinants for a major ship repair yard. Based on 414 cases of ship repairs over a time span of four years at major ship repair yards, by using a GMM model, size, age, and dry-dock days are depicted as the main determining factors behind operating costs. The research also suggests that future studies can focus on investigating the determined parameters on each dry-docking individual element and on examining dry-docking cost geography, comparing similar dry docking projects and elements in different regions.

In the 12th International Conference on Computer and IT Applications in the Maritime Industries, Thomson and Renard (2013) explained the role of shipyards as producers of lifecycle maintenance models. One of the greatest benefits of shipyards using 3-D models is that the models can potentially play a greater role in the lifecycle of their products. They can also gather feedback on the through-life performance of their vessels, which enables optimization opportunities (e.g. steel thickness frame spacing). A lifecycle model could be the first step towards the extension of shipyards in the aspect of providing lifecycle services such as management of technical databases, calculations, preparing and implementing dry-docks and repairs, retrofitting, and training. The article also describes current lifecycle management systems, such as AVEVA NET, which offer gateways for many software systems and 3-D design tools by enabling the extraction and visualization of intelligent documents and datasets and has been used in the oil and gas industry.

5. CLASSIFICATION SOCIETY SOFTWARE REVIEW

5.1 Background, motivation, and aim

Traditionally, classification-society provided rules and simplified, easy-to-use formulas are applied to determine the scantling dimensions of a ship's structure. These formulas still remain useful in the early stage of the design process, but the increase in ship complexity and research in first principal methods has become a driver for class societies and designers to utilize a more rational-based design. While class societies still publish and develop rule-based formulas, such rule-based approaches now exist with guidelines for structural assessment analysis methods that must be applied. Such guidelines specify how to investigate the structure, and what acceptance criteria must be used. Unlike rule-based approaches, the guidelines themselves do not directly specify the final structural dimensions. 3-D finite element (FE) models are extensively used for global and detailed analysis, and thanks to software and hardware updating, model definition (decreasing of mesh size) has been improved with the additional possibility to increase the number of details subject to fine mesh model assessment. Also, the approach to load-cases definitions has changed. In particular for fatigue analysis, the support of software for long-term hydrodynamic loads calculation has been introduced.

Advanced methods used for structural assessment offer to shipyards the opportunity to use a more efficient design recognized and requested by owners. Often, this added value is certified by a classification society with a specific class notation assigned to new buildings and is monitored throughout the ship's life.

General purpose software and tools are not completely able to support the design process without complex and expensive customization to facilitate quick modeling, loading (interaction between hydrodynamic and structural software), and post-processing the results. However, classification society tools are inherently marine-specific. For these reasons, classification societies' tools are evolving to support higher-fidelity analysis and more complex design procedures. Availability of software supporting the design and approval process is advertised as an important service and as a clear index of competence and efficiency. Recent acquisition of the marine software firm NAPA by ClassNK may be considered as an evident interest in expanding and improving the range of services offered to shipyards and ship-owners, including a portfolio of software modeling tools.

The increase of information supporting the approval process has also encouraged classification societies to develop applications for data storage and through-life monitoring. The aim is to create a platform that serves shipyards, subcontractors, and surveyors so that ship owners may efficiently interact not only during the approval process, construction phases, but also the rest of the ship's lifecycle. Advances in technology offer the possibility to maintain in databases product data models representing all details of the vessel's structural history throughout its service life. Not only drawings, support documentation, notes, remarks, and certification would be stored, but also, for particular purposes, models that may be used during ship life for ship monitoring and maintenance for re-fitting assessment and accident support. These applications are developed to guarantee the availability of information but also, thanks to appropriate access control, to ensure intellectual properties, which is very important considering the number of different parties involved in ship design.

Classification society tools were last subject to evaluation by the ISSC Technical Committee IV.2 in 2000. Criteria of analysis defined in that report still remain as good guidelines for the evaluation of tools, but advances in information technology, combined with continued rules development, keep alive the Technical Committee's interest in this particular topic with the intention to also extend the attention to application supporting information storage and sharing during the ship lifecycle.

The aim of this chapter is not to present a benchmark study but to give evidence of how classification societies are extending their offers in terms of software development by covering not only the design stage but also the entire ship life. In Figure 5, a workflow is presented to map typical main activities, parties involved, and tools used as support with evidence of their interactions.

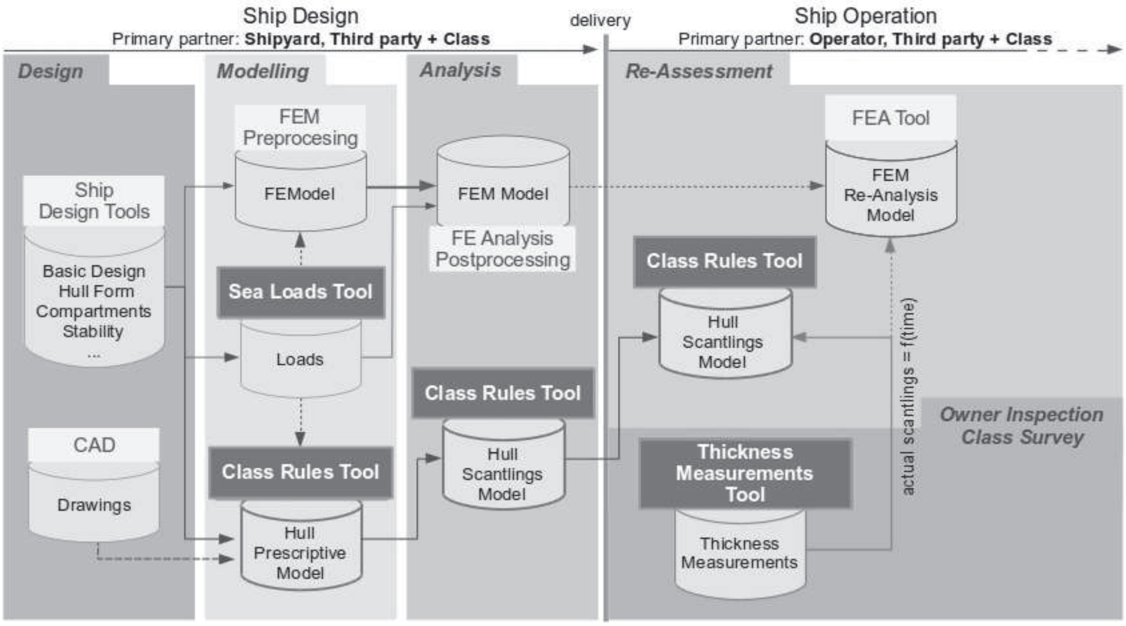

Figure 5. Typical flow of structural information through classification society tools over a ship's lifecycle.

5.2 *Tool analysis*

5.2.1 *Overall functionality*

The software tools provided by the classification societies, which are evaluated in this section, can be divided in two main categories: tools for the assessment process of the ship structure and tools for the Project Lifecycle Management (PLM).

Both the main categories, in turn, can be broken into sub-categories. As for the software tools for scantling assessment of ship structures, all categories have been presented previously in the appendix of the ISSC2000 IV.2–Design Methods:

- Hypertext-based rule search and presentation, which allow the user to quickly find the relevant rules within the full rule text by means of built-in search facilities and cross-references in the form of hyperlinks.
- Calculation of scantlings of structural configurations according to rule requirements. These tools, provided by some classification societies, are designed for the assessment of plates and stiffeners of ship structures according to their rules.
  - 2-D analysis of the hull cross section that allows the user to calculate the cross sectional data, once the user has input the arrangement and dimensions of every structural part making up the ship cross section. Also, some tools are equipped for the assessment of local structure according to the rules.
  - 3-D modeling of parts or of the whole ship structure and direct calculation methods. The user can create a 3-D FE model of ship structures and carry out direct FE calculation for structural verification.
- Data exchange between design and analysis tools.

The Project Lifecycle Management tools can be classified into two sub-categories:

- Database for management of plan approval process information.
- Database for management of ship performances as well as of the performances of the entire fleet.

5.2.2 *Evaluation Criteria*

The evaluation of the software is carried out in two different levels of analysis. The first level is common to both categories of the software. First, the software tool under evaluation is associated with a subcategory in order to identify which is the general functionality of the software. Then, the users to whom the software tool is addressed are identified (i.e. the designer, the shipyard, classification societies' plan approval or surveyor, owner) along with the phase of the design process in which the software tool has been designed to be used (i.e. pre-contractual, preliminary design, functional design, detail design, approval process, monitoring during the construction, warranty and ship life monitoring or ship decommissioning). Other information gathered in this phase of the software tool evaluation is the application field of the software tool, that is, whether the tool has been designed to be used for all types of ships or for a precise category of ships.

After the first level analysis of the software, a second analysis is carried out, for which two sets of questions have been defined: one set related to software tools for scantling assessment, the other related to PLM tools. The evaluation of a software tool is performed, answering each question individually.

Questions related to the evaluation of software tools for the assessment of ship structures are listed below:

- What is the functionality of the software tool?

Software tools for the scantling of the ship structures can be used for different types of analysis or they can be designed for global or local analysis of structures. For this reason, further questions going into more detail are below:

- What are the components of the ship structure that are covered by the software?
  - Do restrictions apply that limit the usage to special types of elements, e.g. longitudinally oriented or to regions like 0.4L mid ship?
  - Which assessment procedures are supported? Minimum scantling according to rules; stresses and displacements based on direct calculations; limit state analysis: first principle design; vibration analysis (eigenvalue and eigenvector, frequency response); fatigue design assessment.
  - Does the system support 2-D or 3-D ship structure models to be applied for the assessment?
- What is the input mode of the software? All tools require input data, either 2-D or 3-D geometry models for carrying out the analysis. In this part of the software evaluation all the input modes are taken into account for each tool. Moreover, the compatibility with other commercial software typically used in the maritime industry has been taken into account, which is described in more in detail below:
  - Does the tool allow a manual input of geometry models and data? If so, is a parametric and/or associative modeling approach supported? How is symmetry handled?
  - Does the tool assist with the input of recommended scantlings from rule calculation software?
  - Does the tool allow the importing of a geometric model from CAD software?
  - Is a possibility function available to import FE models from other FE software?
  - Which types of loads can be taken into account in the analysis? How can the user manage different load cases or combinations thereof in the pre-process phase?
- As for the FE software tools, does the classification society provide an FE solver, or does the society have the direct calculation be carried out using an external solver (e.g. Nastran or Ansys)?
- What are the FE capabilities offered by the tool? Does the FE software allow carrying out special structural analysis (e.g. Smith's method collapse routines, simplified ultimate strength codes)?
- What are the capabilities to export raw data or complete models? As for the FE software, on the one hand, the software sometimes allows the export of the FE model in a special format so that the database can be loaded in other software, or the FE model can be solved by different solvers. On the other hand, the other structural tools sometimes allow to create automatic reports or to export the data and the results in different formats.

With respect to the PML tools, the second level evaluation is carried out, individually answering each of the following questions:

- What is the information taken into account in the database (e.g. drawings, certificates, missing information for the approval of the project, FE models)?
- Does the data management allow all shipbuilding parties (i.e. owner, classification society, shipyard) to interact (e.g. status of remarks, drawing submission)?
- What is the software architecture (i.e. is the software web based)? Is a particular database structure or capability offered for models?
- Does the software integrate with the class societies' through-life inspection, corrosion/gauging data collection, and other through-life tasks? Does the software have the ability to update the design stage geometry/FE model with gauging data to build an "as corroded" model of the vessel in service? Are any lifetime fatigue management tools offered? Are critical areas identified in the software to help surveyors? Are these data shared between similar ships?
- Does the software allow the user to automatically create reports, or to export and exchange data with other PLM software?
- Are special functions built in to support emergency incidents (e.g. grounding, fire, collision)?

5.3 Classification societies tools details

5.3.1 American Bureau of Shipping (ABS)–www.eagle.org

The American Bureau of Shipping (ABS) has developed a series of tools for the strength analysis of ship structures. The **ABS Eagle SAFEHULL** helps designers, shipyards, and engineers of the classification society carry out the scantling calculation according to the rule requirements. The software allows a 2-D analysis of hull cross sections as well as a 3-D modeling of parts of the ship or of the entire ship structure. It can be used in the analysis of bulk carriers, containerships, and tankers that are not built in accordance to the Common Structural Rules. To help the engineers in the structural scantling of bulk carriers and tankers that are designed in accordance with the Common Structural Rules, ABS provides the **ABS Eagle CSR.** This software allows the user to perform the same analyses that can be carried out using the **ABS Eagle SAFEHULL**, but the results are checked according to the Common Structural Rules. The software is used in several design phases, from the pre-contractual phase until the detail design and approval process. The parts of the ship that can be analyzed are the hull cross sections (in 2-D analysis) and the three cargo hold block centered around midship (in 3-D analysis). In the pre-processing phase of the FE model, *SAFEHULL* is able to import the FE 3-D model, as well as the 3-D geometric model, that is created in other software. It is also able to identify tanks in the 3-D model, and the user can apply loads and external pressures, which mimic full and light drafts, to the FE model. The FE analysis is solved by Nastran and *SAFEHULL* post-processes, and the results can be displayed in tabular or colored contour formats.

Two modules have been developed for evaluating an LNG vessel's design and an LGC vessel's design: *SAFEHULL–LNG* and *LGC ISE*, respectively. Both modules allow the user to carry out the same analyses that are available in *SAFEHULL*, but the scantling of ship structures is done according to the classification society rules for LNG and LCG vessels. ABS assigns the SAFEHULL (SH) notation to oil or fuel oil carriers, bulk or ore carriers, combination carriers, and container carriers that are designed according to Part 5C, Chapters 1, 3, and 5 of the ABS Rules for Building and Classing Steel Vessels, respectively. Also, the SH notation may be assigned to membrane tank LNG carriers designed in accordance with Part 5C, Chapter 12 of the ABS Rules for Building and Classing Steel Vessels. The SH notation applies to container vessels over 130 m; bulk carriers, oil carriers, and membrane tank LNG carriers over 150 m; and liquefied gas carriers with independent tanks over 90 m in length. The requirements of these portions of the rules are collectively referred to as the SAFEHULL Criteria.

ABS provides the **ABS Eagle DLA/SFA Analysis System** which integrates the dynamic load approach and the spectral fatigue analysis in a software package that includes the major analysis components. The software is provided to shipyards, designers, and engineers of the classification societies and can only be used for ship-shaped hull forms. A seakeeping analysis of the ship can be carried out through the application of 3-D potential theory based on hydrodynamic analysis in frequency or time domain. A probability analysis of wave and ship response statistics follows the seakeeping analysis. The *DLA/SFA* tool provides several modules for the assessment of loads for liquid, bulk and container cargoes: the buckling and yielding strength assessment and a full spectral-based fatigue analysis. The FE analysis is carried out in Nastran, and the results can be post-processed within the tool environment. ABS assigns the SAFEHULL Dynamic Loading Approach class notation to vessels that have been evaluated using an enhanced structural analysis procedure and criteria for calculating and evaluating the behavior of hull structures under dynamic loading conditions. Such vessels must be built in accordance with plans approved on the basis of the results of such analysis, in addition to full compliance with the other requirements of the rules. Spectral Fatigue Analysis (SFA) notation is assigned to vessels on which Spectral Fatigue Analysis is performed in accordance with an acceptable procedure and criteria, and the vessel is built in accordance with plans approved on the basis of the results of such analysis. The vessel will be distinguished in the Record by the notation, SFA(years). The notation, SFA(years), denotes that the designated fatigue life value is equal to 20 years or greater. The (years) refers to the designated fatigue life equal to 20 years or more (in 5-year increments), as specified by the applicant.

Project management databases are provided by ABS to be used in the design phase, in the construction phase, and during the operation phase of the ship. These databases are all web based, and they are used by designers, shipyards, ABS engineers, and surveyors. The **ABS Eagle Web Calc Structures and Machinery** software packages provide the engineers with instant calculations for hull and machinery according to the ABS rule requirements.

The **Rule Manager** is a hypertext based rule search that allows to quickly identify the applicable ABS Rules and IMO requirements for a project based on parameters including vessel type, service, scantling length, and contract date. This software is used in all the design phases as well as in the monitoring of the ship during its whole life.

The **ABS Eagle Engineering Manager** is a PLM tool for managing plan approval information as drawing comments, outstanding comment status, certificates, missing information for the approval of the projects, and drawings throughout the approval process. The software can also be used by owners and vendors, and it has been designed for managing documents of all types of ships. During the operation phase of the ship, the *ABS Eagle* survey manager helps the owners and shipyards, as well as the engineers and the surveyors of the classification society, to manage all documents regarding the fleet information and survey history, due, and status.

ABS also provides a tool for the Lifecycle Management of the ship **NS5 Enterprise**. The software helps the user in the management of ship operations, from regulatory requirements and crewing to payroll, purchasing, and planned maintenance. ABS does not provide any special class notation related to the usage of these databases during the design and construction phases.

5.3.2 Bureau Veritas (BV)–www.bureauveritas.com

VeriSTAR Hull 5 is the latest release of Bureau Veritas (BV) software for structural analysis by means of a 3-D FE model calculation. It is based on a customization of the general FE tool FEMAP. Both NX Nastran and MSC Nastran are supported as solvers. Using FEMAP as pre- and post-processors allows the user to access all functionalities for geometry modeling, which are available through the standard FEMAP interface. It can apply rules for not only CSR and CSR-H for bulk carriers and double hull oil tankers, but also for BV steel structures and offshore units. Loads and boundary conditions are automatically applied in accordance with the rules requirements. *VeriSTAR* can carry out the global strength assessment of cargo hold structures according to yielding and buckling criteria, stress assessment of local detailed using local refinement, and fatigue strength assessment.

For ship structural assessment based on complete ship model description, BV offers the tool **VeriSTAR CSM** (Complete Ship Model), integrating the BV Rules standard calculation and FE analysis under a common interface. It is mostly intended for container and RORO vessels and is valid for both new building and existing ships, and it stores data in a ship-dedicated database. *VeriSTAR CSM* is a tool thought to be used from an early stage of design and maintained during the ship's life. **MARS 2000**, freely distributed, offers functions to approve scantlings of plating and stiffeners of any cross-section or transverse bulkhead according to BV Rules and IACS Common Structural (CS) Rules for Bulk Carriers and Tankers.

Other stand-alone application for specific topics are provided below:
- **RUDDER**: for scantling of rudders according to BV and IACS CS Rules for Bulk Carriers.
- **BULK**: for transverse bulkheads and the double bottom of bulk carrier structural strength calculation
- **LIRA**: a shaft alignment calculation tool based on the transfer matrix method, which includes reverse calculations based on measurements.
- **STEEL**: a 3-D beam analysis program based on the displacement method that is a general purpose tool, not linked to specific rules or regulations, but suited to be used in various fields of the marine industry.

Multiplicity of information related to approval and inspection in new construction activity is managed by BV and BV costumers with the project management tool **VeriSTAR Project Management** (VPM), a web-based collaborative platform in which all parties, depending on the assigned rights, can review and exchange information during the ship's design and construction. Design review, product certification, and survey of construction are covered, and access to project files, status of design review, comments, certification, etc. are easily available through a personalized interface.

VeriSTAR AIM is an open, web-based system designed to improve inspection management and information control during the ship's life after delivery. The system provides not only the storage and management of asset documentation, anomalies and maintenance history, and statistics, but also access to the available calculation models (e.g. structure, stability).

The service **VeriSTAR-HLC** (Hull Lifecycle) supports hull structure monitoring during the vessel's service life. Vessels operated under this program may be assigned the class notation VeriSTAR-HLC. Based on a 3-D model representation of the ship, the core of the system is the management of the inspection results such measurements, cracks data, and coating condition. The tools is based on the OpenHCM format for the exchange of structural inspection results. The underlying 3-D models of the ship structure may be created by the 3-D modeler out of ship's main drawings manually or with the possibility to import shipyard CAD files including IGES and DXF formats.

5.3.3 China Classification Society (CCS)–www.ccs.org.cn

Aiming at safety management, energy saving, and environmental protection, the China Classification Society (CCS) has been continuously developing a comprehensive set of software to facilitate product lifecycle management for the marine industry. The software system, which is collectively named *COMPASS*, can help designers, shipyards, and engineers of classification societies carry out rule-based scantling calculations or corresponding design optimizations.

COMPASS-WALCS is 3-D wave loads calculation software with four modules: linear wave loads analysis, nonlinear wave loads analysis, linear hydro-elastic analysis, and nonlinear hydro-elastic analysis. The software can be applied to 3-D wave loads calculations for floating bodies with zero forward speed and to ships with conventional forward speed, and it provides basic references for determining wave loads' design value for ocean engineering in all types of design conditions. It can also be used for analysis of springing and whipping loads induced by nonlinear wave loads.

COMPASS-RULES is a computer assessing system for sea-going ships in accordance with CCS Rules for Classification of Sea-Going Steel Ships, IACS URs; Regulations for Statutory Surveys of Ships and Offshore Installations by MSA of PRC; relevant IMO conventions and codes; and other updated technical standards. The software has been widely and successfully applied in plan approval, rules development and research, auxiliary design, and shipping safety assessment. The software is comprised of more than 20 functional modules categorized into four sub-systems: performance calculation, structure calculation, shafting calculation, and electrical calculation systems.

COMPASS-CSR-SDP is a structural design and assessment program for bulk carriers and oil tankers, compliant with IACS CSR rules. The software effectively provides all CSR prescriptive rule-required calculation capabilities for all main structures including the cargo hold region, bow, stern, machinery space, and superstructures.

COMPASS-CSR-DSA is direct structural analysis software developed in accordance with CSR Rules for Bulk Carriers and Oil Tankers based on the MSC.Patran platform. With the software's powerful capabilities of automatic loading, boundary constraining, corrosion deduction, mesh refinement, and buckling panel definition and a rich structural database of marine structure profiles, it can greatly reduce calculation time in FE modeling, increase analysis efficiency, and enable engineers to perform CSR rule required FE analysis both quickly and accurately.

COMPASS-HCSR-SDP is prescriptive rule check software with full coverage of Harmonized Common Structure Rules (HCSR) prescriptive requirements and of the whole ship. The software can be used to perform rule required assessments of hull girder yielding, ultimate and residual strength, scantling requirement, buckling strength, fatigue strength, bow impact, bottom slamming, tank sloshing, bulk carrier grab, steel coil, and other special requirements. With an integrated platform of parametric modeling, streamlined processing, and optimized numerical calculation methods, it effectively enables engineers to perform HCSR rule required assessment both quickly and accurately.

COMPASS-HCSR-DSA is direct strength analysis software with full coverage of HCSR direct strength analysis requirements including yielding, buckling, and fatigue assessment of the entire cargo area. The software is based on the same platform and with same set of uniform capabilities and user interfaces as CSR *DSA* software. It is designed in accordance with the industry tradition which achieves high levels of practicability, usability, flexibility, and efficiency and can effectively enable engineers to perform HCSR rule required FE analysis both quickly and accurately in all stages of ship design, ship development, plan approval, and inspection. Additionally, two structural-based through-life support packages are offered: *COMPASS-ERS* is a consulting service software to facilitate the society's emergency response service and *COMPASS-CAP* is a condition assessment program. *COMPASS-CAP* is provided as a technical service for owners with no relation to the class of ship.

5.3.4 Croatian Register of Shipping (CRS)–www.crs.hr

The Croatian Register of Shipping (Hrvatski Registar Brodova, or CRS) has developed several tools for the strength analysis of ship structures as well as product lifecycle management databases. **CREST** is a software package that has been designed for carrying out 2-D analysis of ship structures. It allows the user to verify the compliance of the ship structures with CRS rules in the preliminary design phases and during the approval process. The tool supports the structure design by performing calculations for the scantling of ship structures. The geometric model can either be defined manually by the user in the software environment or imported from MAESTRO. Automatic reports can be created after the analyses. **CREST CSR BC** and **CREST CSR T** are two releases of the *CREST* software that are designed for verifying the compliance with the CSR of the cross sections of bulk carriers and double hull oil tankers, respectively. The *ARGOS* tool has been developed for performing intact and damage stability calculations and longitudinal strength calculations. Both analyses are carried out in accordance to the CRS rules. The software is used by designers, shipyards, and class plan approval and can be used for any type of ship.

As for the PLM databases, **ZEON** is a web-based software for the management of plan approval process. It has been designed to simplify and improve the documents exchanges among the designers and shipyards, the CRS plan approval department, and the CRS surveyors. SPP is another tool provided by the CRS. This tool is a web-based service, useful for sharing information and documents about the ship status throughout its life. The software is used by the ship managers, owner, CRS surveyors, and flag authority, and it allows users to share and review documents and certificates, such as the data about the corrosion of plating, during the through-life inspections. Both ZEON and SPP software are designed to be used for any type of ship, and all data gathered using the software are stored in web-based servers.

5.3.5 DNV–GL

5.3.5.1 Introductory comment

The following information is based on a guided interview on the premises of DNV–GL in July 2014 and on an additional study of publications related to the software tools being documented. At that time, the merger of the two former classification societies was approved but not completed. The future strategy regarding the software tools offered to customers and being used in-house was not developed. Therefore, it was decided to fully focus on the software that was available at that time and to discuss the software provided by DNV and GL in separate sections.

5.3.5.2 Det Norske Veritas (DNV)–www.dnvgl.com

Det Norske Veritas (DNV) has developed a series of software packages for supporting the assessment process of ship structures.

Nauticus Hull consists of a series of modules that are combined in a workbench. In its basic configuration, the *Nauticus Hull* system provides for the rule check software that allows the user to verify the ship according to DNV rules for both the classification of ships and the IACS Common Structural Rules for Tankers and Bulk Carriers. All modules of the *Nauticus Hull* workbench are designed to be used in several design phases, from the pre-contractual phase to the detail design and approval process phases. It is used by engineers of design offices and shipyards, engineers of the classification society, and the owners. In the following paragraphs, the different *Nauticus Hull* modules are briefly discussed.

The **Rule Check software** is a generic design tool for the initial hull girder design and optimization. It provides engineers with calculations for ship hull structures according to DNV rule requirements and to the IACS Common Structural Rules for tankers and bulk carriers. The initial information about the ship structures is entered into the concept model of *Nauticus Hull* and can then be used in all the other modules of the system. The design of the ship cross sections and transverse bulkheads is performed using the **Section Scantlings Program.** By means of this tool, the user can perform a 2-D analysis of the ship structures. The hull girder longitudinal strength, the local strength, and the buckling of plates and stiffeners can be verified according to the rule requirement. Moreover, shear flow calculations can be carried out by means of that module. All model data defined using the *Section Scantlings Program* can be imported in other modules for defining a 3-D model for FE analysis. Fatigue analyses of longitudinals are carried out directly in the *Section Scantlings Program* environment.

The **High Speed Light Craft Software** package provides engineers with rule checking and structural analysis carried out according to DNV rules for high speed and light crafts. The software supports mono-hull as well as catamaran designs, including non-symmetrical cross sections, and allows for calculating the section properties and shear flow distribution for vertical force, horizontal force, and torsional moment.

For modeling and analyzing the 3-D beam structures and for carrying out a first assessment of ship structures, DNV has developed *3DBeam* software. This tool can be used as a module of *Nauticus Hull* or as a stand-alone program. Nonlinear responses from structures such as wires (tension only) or gaps between members of the structure can also be considered. The geometry can be also defined in a Microsoft Excel spread sheet and then imported into **3DBeam**. Loads are generated during the pre-processing phase of the model definition, and loads due to hydrostatic pressure, inertia, wind, snow, and temperature can be taken into account. All loads applied to the model, as well as boundary conditions, can be graphically shown. In the post-processing phase, the results of the analyses (i.e. deflections, shear force, and bending moments) can be displayed graphically in the geometric model or numerically in a table. All results can be exported in a Microsoft Excel format. Moreover, reports can be created automatically.

For analyzing and modeling methods and devices for securing containers on ships, and for assessing forces on containers during transport voyages, DNV has developed the **Container Securing Software**. This tool performs the analyses of the container blocks and securing methods, according to DNV Rules for Ships, once the structure has been defined and the environmental load combinations (wind forces and accelerations) have been applied to the structure. The geometrical model can also be defined using an MS Excel spreadsheet and then imported into the *Nauticus Hull* environment. The analytical solution is carried out by means of *3DBeam* software, and the results are post-processed in *Nauticus Hull*. Different solutions of securing methods and devices can be compared performing the analyses using this tool.

The **Buckling Assessment–PULS** is a software package that has been developed by DNV for carrying out buckling strength evaluation of ships and offshore structures. The tool is able to perform a strength assessment of stiffened thin plate panels and stiffened and unstiffened cylindrical shells according to DNV rules. The analyses take into account the simultaneous action of in-plane loads, such as bi-axial tension, compression, and shear stresses, which can be combined with lateral pressures. The results of the analyses are visualized in the *PULS Advanced Viewer*, a module that providing 3-D graphics of buckling modes and redistributed stress patterns.

Direct strength analysis of ship structures can be carried out using *Nauticus Hull* and **Sesam GeniE**. The latter is a software package provided for 3-D modeling and direct FE analysis of floating structures made of beams and/or plates. The geometry of the cargo holds to analyze is defined directly in the *Sesam GeniE* environment, or it can be defined according to the section data imported from the *Section Scantlings Program*. The loads are applied directly in the *Sesam GeniE* interface; otherwise, rule load cases, boundary conditions, and corrosion additions are defined in the *Nauticus Hull* environment. Results of the analyses are graphically shown in the 3-D models, and reports are automatically generated. The integrated code checks automatically verify the compliance of the structures with DNV Rules for Ships. The FE model can be imported by other FE software. The analyses are carried out in *Sestra*, an FE solver for linear structural analyses such as static analysis, free and forced vibration analysis in frequency and time domain, and superelement analysis. The FE analysis can also be exported in other formats for solving the calculation using external solvers such as Nastran.

DNV assigns the *Nauticus* class notation to the vessels whose structures of the midship area have been designed using a procedure based on FE calculations. The class notation also covers extended requirements such as fatigue calculations for longitudinal-frame connections in several critical areas of the vessel. The notation is mandatory for oil tankers, bulk carriers, and container carriers, with lengths more than 190 m.

The **DNV Exchange** is a web-based PLM software provided by DNV for exchanging and sharing information among the different stakeholders of a ship's construction. The database can be also installed directly on a PC using a stand-alone license. It is designed to be used in all design phases. The information that is taken into account are drawings, remarks, certificates, missing information for the approval of the project, and in the stand-alone version, sketches and photos. Web access to the 3-D model of the vessel hull structure allows the user to carry out calculations of coating areas and steel weights. The 3-D model is also used for viewing the coating status, thickness measurements, and renewal estimations. The model is also designed to be used by surveyors for identifying areas to be given special attention during the maintenance. The software creates reports automatically, documenting the results of analyses and inspections.

5.3.5.3 Germanischer Lloyd (GL)

Germanischer Lloyd (GL) offers four integrated tools that can be applied in the modeling and analysis during the ship design and the operational phases of a vessel. The tools are not specific to any ship type. The modeling of the ship hull structure is performed with **POSEIDON,** which then determines or evaluates the scantlings of all longitudinal and transversal structural components, taking into account local and global loads. Yield, buckling, and fatigue assessments are performed. The dimensioning is checked against all relevant GL rules for hull structure approval, including CSR. The initial 2-D modeling approach in the form of hull cross sections allows a fast build-up of a structure concept model. For special ships like container vessels and bulkers, parameterized templates serve to generate a full topological description in a very short time by specifying few parameters and describing specific the ship the calculations that will be performed. At this stage, the designer does not have to specify any scantlings of plates and stiffeners because *POSEIDON* offers the unique approach of calculating the according values by automatically observing all loading conditions, which include global (e.g. hull bending) as well as local (e.g. pressure heads) loads. The calculations are performed in an automated, iterative process until convergence is reached. All calculated scantlings can be further analyzed by the designer by applying the built-in explanation function, which links to the relevant rules that have been applied, including the specific results. This allows the designer to get a sound insight of the necessary scantlings of the design. Due to the fully topological modeling approach, compartments are generated automatically while the user must supply a minimum amount of additional data such as contents, maximum pressure head, etc. Additionally, changes to the ship hull form, the ship internal subdivision, and the structural design, which occur frequently in the early design process, can be incorporated easily, while the required updated scantlings are recalculated automatically. Furthermore, integrated model checks guarantee that unrealistic or error prone ship structure models are not being applied for the calculation of the scantlings. Interfaces exist to import the hull form (IGES) and compartmentation information from the NAPA Steel system. The 2-D cross sections (which can be copied to other sections and adapt to changes, e.g. changes to the hull form geometry, automatically) serve as the basis for built-up 3-D cargo hold models that perform FE analysis by checking yield, buckling, and fatigue. The 3-D modeling functions are not restricted to the midship region, but rather, they allow for a complete 3-D modeling of the ship. For the design of hatch covers, an integrated beam and grillage analysis can be performed. The *POSEIDON* data model is stored in a single file, and an API allows the user to get external access to the data. The *POSEIDON* data model also serves to calculate the remaining hull structure capacities in case of damage, in which case, a function is applied in the emergency response service.

The special program **ShipLoad** calculates the loads on the structure in a seaway for which numerous loading conditions and wave data are to be observed. The output is either used as input to *POSEIDON* 3-D FE analysis or can be applied to a global FE model to be analysed by any external FE analysis package.

The program **Pegasus** can be applied to manage hull structure thickness measurements in the ship operation phase. The program is capable of developing a ship specific measurement strategy that results in a detailed measurement plan, which guides a person's measurement taking. Measurement data are stored in a database that automatically links the measurements to structural components. By this process, taking the actual scantlings into account, it is possible to reassess the capability of the ship hull structure. Furthermore, maximum diminution parameters serve to rationally evaluate the status of the structure as well as perform detailed statistical analysis.

ShipManager Hull is a tool that can aid the ship operator in monitoring the structural condition of the ships in a fleet. The program builds upon a hull lifecycle model (HCM), which is derived from the prescriptive model generated by *POSEIDON*. All data relevant to be managed during the ship lifecycle concerning the hull structure can be stored and visualized as well as reported upon request. This includes scantling values ranging from as built to any number of actual values in a timeline. Additionally, the status of the coating can be documented with respect to specific structural components or regions. The system is capable of handling data, documents, and pictures, and it shows the conditions found during inspections. Regions can be highlighted where special attention should be given in future services.

5.3.6 Korean Register of Shipping (KR)–www.krs.co.kr

Sea Trust-RuleScant is the main Korean Register of Shipping (KR) software used for supporting ship structural design and strength assessment according KR Rules, including also IACS CSR for Bulk Carriers and Oil Tankers and enabling certification with CSR-H class notation. Software functionalities cover hull cross section generation and 3-D modeling of parts of the ship or of the whole ship. The input of model geometry and data is supported by the possibility of import geometric models from IGES, STEP, and DXF, but it is also assisted by tools (e.g. dialogs, menus, and spreadsheets similar to Microsoft Excel), providing recommended scantlings. FE models may be imported from MSC NASTRAN using *RuleScant* for the automatic loading generation based on rule requirements. The analysis is carried out by external software such as MSC-NASTRAN or IPSAP. Post-processing capabilities include buckling and fatigue assessment.

New ship designs requiring a complete ship model may take advantages from the extended capabilities offered by **Sea Trust-ISTAS** (Integrated Structural Analysis System), an integrated software system that includes the components for the direct structural analysis. The system includes specialized modules for ship motion and wave loads analysis; stochastic analysis and design loads generation; solver for FEA analysis; simulation of ship motions, waves, stress, and displacement; and buckling and ultimate strength assessment. Characteristics of the ship, such as hull form (limited to symmetric types) and weight distribution (generated with whole ship structural model), are used in the seakeeping analysis (linear frequency domain) to obtain dynamic loads based on a 3-D Panel theory. With a return period corresponding to the ship's life, stochastic analysis is carried out to obtain the most probable extreme value. Design loads obtained from hydrodynamic analysis are transferred automatically to the global ship FE model.

Using **Sea Trust-FANSYS**, spectral fatigue analysis is performed to evaluate the fatigue life directly with stress results from whole ship analysis at all heading angles and wave frequencies. Fatigue loads, in conjunction with a very fine mesh for evaluation of the hot spot stresses, allows the calculation of fatigue life of the vessel's specific structure. Also, simplified fatigue analysis method is supported. Fatigue loads are estimated from KR Rules formulas, and then the fatigue levels for longitudinals, connections, and hopper knuckle parts are calculated. Sea Trust(FSA 1), Sea Trust(FSA 2), or Sea Trust(FSA 3) class notations may be assigned to vessels assessed with this software.

Management of thickness measurement data and relevant survey information are supported by **Sea Trust-TM**.

Sea Trust-SLM, or KR Ship Lifecycle Management System, provides a 3-D ship model in which all information during ship design, construction, operation, inspection, repair, and recycling can be stored for easy access. It can be interfaced with the customer's management system, and ship builder, owners, operators, and surveyors can share and use information such geometric model, drawings, product specification, maintenance data, etc.

Lloyd's Register (LR)–www.lr.org

RulesCalc has been developed for the assessment of ship structural designs according to Lloyd's Register (LR) rules and regulations for the classification of ships. It can be used as a stand-alone system or in conjunction with other design software packages, including NAPA, Tribon, and LR's *ShipRight* Structure Design Assessment (SDA). Project information is recorded in a hierarchically organized using the analogy of a family tree in which there are parent branches or folders and sub-branches or sub-folders that are children of the parent. This architecture allows the program to perform various assessments, such as local scaling or 2-D ship section analysis, on the basis of consistent data inputted once at the beginning of the design. This data is editable, if necessary, during its development. Any calculation performed is tracked and visible in the graphical interface with the clear reference to rules applied.

RulesCalc, used in conjunction with **Rulefinder**, an interactive PC-based software system providing a searchable access to a library of the latest requirements from both LR and IMO, gives the user the immediate evidence not only to calculation results but also to rules requirements and formulas.

The complete end-to-end assessment of ship structure against LR's ShipRight **SDA** notation and Fatigue Design Assessment procedures (**FDA** notation) is supported by the **ShipRight** 3-D FE analysis tool. It includes features such as an interface with NASTRAN and PATRAN FE model tools, enhanced calculation of ship motions and hydrodynamic loads, advanced spectral analysis and incorporation of 100A1, and IACS North Atlantic wave environments.

Transferability of electronic ship models from commonly used CAD packages (e.g. SmartMarine 3D–Intergraph, NAPA Steel, Tribon-Aveva, AutoCAD, and IGES format for structures and hull forms) to LR applications is also enabled by the software **Interface Toolkit**.

Owners and managers of an LR-classed fleet may take advantage of **Class Direct**, a free service that provides data for a single ship or an entire fleet that is relevant to survey status and historical records. *Class Direct* may also contain thickness measurements reports created with **Argonaut**, a dedicated tool developed by LR for this purpose.

5.3.7 Nippon Kaiji Kyokai (ClassNK)–www.classnk.com

Nippon Kaiji Kyokai (ClassNK) has a comprehensive system that aims to support a ship's life. *PrimeShip* is the collective name for the software systems, guidance, and data services developed and offered by ClassNK. The software groups are categorized as Hull, Machinery, Operation, and Maintenance, and software related to hull and structural design are described below.

PrimeShip-HULL (HCSR) supports prescriptive rules and direct strength calculations, and it creates models and performs strength analyses from stem to stern in accordance with the harmonized CSR (HCSR). It allows the designer and yard to rapidly carry out case studies of potential designs and optimization. It is a new software, compared to the previous **PrimeShip-HULL** version, by combining the rule calculation and DSA analysis software with newly developed interfaces for data linkage with commercial CAD software. The interfaces are XML-based and developed by PrimeShip CAD Interface Project composed with ClassNK and members from 13 Japanese shipyards and 3 software venders. These have been opened on the ClassNK web site (https://www.ps-cad.jp/outside/index.html). And these provide linkages between CSR calculation software PrimeShip-HULL and commercial naval architecture design packages, such as AVEVA, NUPAS, CADMATIC and NAPA STEEL, and the duplication of modeling work on both a package possessed by a yard and class rule software can be reduced. Geometry models and additional data can be input manually as well. The rule calculation assists taking input from rule calculation software and generating recommended scantlings. For DSA analysis, both HyperWorks-based and Patran-based *PrimeShip-HULL (HCSR)* are developed and the original functions of the base FE software are available. DSA analyses are carried out using Nastran, Raddioss, or Optistruct. Outputs are geometry, scantlings, and other data, and reports are automatically generated.

PrimeShip-HULL (Rules) is a rule calculation software for hull structures. This free software allows designers to calculate the requirements for structural members in accordance with IACS-CSR for bulk carriers and oil tankers and Part C of ClassNK Rules. It is comprised of three software programs for specific rule sets: **PrimeShip-HULL(Rules)/NK Rules** for ClassNK Rules, **PrimeShip-HULL(Rules)/CSR Bulk Carrier** for IACS CSR for Bulk Carriers, and **PrimeShip-HULL(Rules)/CSR Tanker** for IACS CSR for Double Hull Oil Tankers. It has functionalities of a manually entered geometry models and data, or it can import geometry models from CAD software and a quick calculation for strength members from cross sections to specific local members. It can then create a report in ClassNK required formats.

PrimeShip-HULL (DSA) is a Patran-based FE direct strength assessment system in compliance with the IACS-CSR for Bulk Carriers and Oil Tankers and Part C of ClassNK Rules. It includes three dedicated software programs for specific rule sets: **PrimeShip-HULL(DSA)/CSR** for IACS CSR for Bulk Carriers and Tankers, **PrimeShip-HULL(DSA)/Guidelines** for ClassNK Guidelines for Container Ships, etc., and **PrimeShip-HULL(DSA)/Ore Carriers** for the ore carrier edition in accordance with ClassNK Rules. It supports strength assessment for bulk carriers, oil/chemical tankers, and container ships for designers, yards, and the class approval process. It has functionalities of an automatic identification of structural members and compartments. Load cases in accordance with the specific rules and guidelines can be taken into account, and recommended scantlings are available.

PrimeShip-HULLCare is a hull maintenance information service developed by ClassNK. It provides ship owners with plate thickness measurement result records and hull maintenance information on ClassNK's web site. It helps make ship maintenance planning an easy process and supports an enhanced survey program (ESP) for ships. Users are able to view the information with **PrimeShip-HullCare/2D Internet** and **PrimeShip-HullCare/3D Model**. The former of these contains significant condition assessment and repair data including steel thickness at measured locations, photographs taken during inspections, specifications and plans for repairs, paint maintenance, condition assessment scheme reports, and hold frame replacement requirements for existing bulk carriers of IACS S31 requirements. **The latter of these,** which is an optional service, provides an easy understanding of the ship's condition with a rotatable and zoomable 3-D model. It also allows the evaluation of a current section modulus by using up-to-date thickness measurement records.

NK-PASS is a web-based system for plan approval status service, which supports designers, yards, and class to submit e-drawings and manage approval process. It can manage submitted drawings, comments, and their responses. Different menus for shipbuilders, machinery manufacturers, and design firms are offered, and users can be registered in a department/section unit.

NK-SHIPS, a web-based service for owners and operators, is designed to retrieve vital information for ship maintenance and management, such as survey status, periodical survey items and due dates, survey history, survey records, and ISM/ISPS audit status, that assists in the effective maintenance and management of ships.

ClassNK Archive Centre (As-Built Drawings Storage Service) is a database for the management of the ship's drawings. It provides an integrated management system of the ship's drawings using cloud computing, which can be accessed through the internet. The information, like confidential drawings, can be securely and effectively transferred to the interested parties in case of emergencies.

5.3.8 Polish Register of Shipping (PRS)–www.prs.pl

The Polish Register of Shipping (POLSKI REJESTR STATKÓW S.A., or PRS) has developed in-house software for supporting surveyors in the approval process of the related technical documentation. These tools are used by the PRS plan approval department and by the surveyors during the management of the documents and information about new constructions or ships in services. As for the Product Lifecycle Management databases, the key programs provided to the surveyors and PRS plan approval department for supporting their work are *SurveyPRS*, *NNB*, and *INAD*. These are web-based systems that allow a hypertext-based rule search to be performed.

The **SurveyPRS** is oriented to support the surveyors in the exchange of information, drawings, certificates, remarks, and missing information. It was designed to be used during the construction phase of new ships and during the operational phase until it is dismissed. The *NNB* and *INAD* are used during the entire life of the ship, starting from the pre-contractual design phase until its dismissal. The **NNB** tool is used for the exchange of the certificates issued by PRS between the surveyors and the plan approval department and between the shipyard and the owner. The **INAD** tool allows the exchange of information between the surveyors and the approval department of the classification society of the drawings and of the remarks and missing information about a ship under construction or in exercise.

As for the tools for the scantling assessment of ship structures, PRS developed two tools used by the surveyors and approval department of the classification society as well as by the ship owner. The **CSR_PRS** is designed for the strength calculation of ship structures according to the common structural rules. The Research and Development department of PRS is developing in this period a new **HCSR_PRS** tool that is designed for the scantling assessment of ship structures according to the new Harmonized Common Structural Rules. Both tools can verify the hull structures of the oil tankers and bulk carriers and allow the user to carry out the scantling assessments of all parts of the ship structures. Calculations for the minimum scantling of the structures, in compliance with the rules, as well as the 2-D analysis of the cross section of the ship hull, can be carried out. Moreover some tools have been implemented in the *CSR_PRS* and *HCSR_PRS* software to carry out direct calculation of strength of local structure, fatigue analysis, buckling analyses, and ultimate strength analysis. These tools allow the user to import an FE model created with other software and to define its element parameters. The load condition of the FE model can be defined according to the HCSR rules. The FE analyses are carried out by means of NASTRAN, and the results can be analysed by the **LOADER** and **LOADERBRIDGE** applications. The software includes automated reporting functions.

WINSEA is a tool for supporting the surveyors of PRS in the approval process of ship technical documentation. It allows the user to carry out scantling assessment of ship structures according to PRS rules. By means of this software, a 2-D analysis of the hull cross section can be carried out. The model geometry can be input directly in the software and a limit state analysis can be performed. The load conditions for all the analyses are defined according to the classification society rules. Automated reporting functionalities are provided.

STAB_PRS is a tool that allows the owners to carry out stability calculation for RORO carriers, container ships, and bulk carriers. The software provides immediate calculations for verifying the stability condition and the strength calculation in the loading and unloading process in day-to-day operations. The assessment can be carried out in both intact and damage conditions.

5.3.9 Registro Italiano Navale (RINA)–www.rina.org

Leonardo Hull 2-D (LH2D), a Registro Italiano Navale (RINA) tool for 2-D structural analysis, has been continuously updated, following rules development, including specific calculation capabilities such as structure verification in ultimate strength conditions and torsion checks of ships with large deck openings, as in the case of container ships.

Data inputted in Leonardo Hull 2-D may be directly imported into **Leonardo Hull 3-D** (LH3D), the tool dedicated to FE analysis. The 2-D section is automatically extruded, and the user is enabled to complete the model by specialized features for modeling structures, such as bulkheads, stools, and trunks, specifically tailored for ship design. Loads are automatically generated. According RINA and IACS common structural rules, the Finite Element Model (FEM) analysis is performed via a two stage approach: the analysis of a hull portion extended over three cargo hold lengths through a coarse mesh model and a more detailed check of specified areas where finer mesh may be automatically generated. Rules checks are automatically performed through the post-processing results of calculations based on the MSC-NASTRAN solver.

LH2D and *LH3D* in particular can used both in the design stage and also during ship’s life-cycle. They support a program of planned maintenance management based on the programmed updating of hull scantlings in accordance with survey measurements, thereby facilitating the accurate prediction of corrosion rates and steel renewal dates.

The use of FEM is certified by RINA with the assignment of the additional class notation **STAR HULL NB** for new building and with the additional class notation **STAR HULL** in case of the creation of the model for structural maintenance management. Existing ships may also take advantage of the additional service **Technical Advisor,** offered by RINA, in which an expert team, thanks to the availability of ship information, may give immediate support in emergency situations such as collisions, groundings, fire, explosions, and oil spills.

RINA also offers as a stand-alone tool the software application *Advance Buckling Check* (ABC), which performs direct calculations for thin walled plated construction. The non-linear, large deflection plate theory of Marguerre and von Karman is applied, as prescribed by CSR for Oil Tanker.

The approval process is supported by the software application **Leonardo DRAW**, a website that gives shipyards access to updated information relevant to their drawing approval status.

Information relevant to RINA class fleets is available throughout **Leonardo INFO**. It is organized into two environments: “Public,” which is available to everyone and provides general data, and “Private,” which is available only to RINA clients showing technical data, status of survey, certificates, historical survey status, and survey reports.

5.4 Conclusions and future challenges

The software overview presented, compared to the one reported in ISSC 2000, shows a clear development of class society tools. Some tools have been simply updated according to new rule requirement. In particular, the creation of both CSR and CSR-H have been an important challenge as entirely new rule sets have been created. However, new features have also been introduced in order to extend the support to designers, surveyors, and ship owners.

CSR and CSR-H also defined a new scenario that creates common rules, among which a class societies compete in terms of support offered to shipyards and ship owners. As the rules are common, designers may choose the software to use independently from the classification society in charge of the approval. Criteria for such software selection would include accurate analysis criteria, evaluating additional software capabilities, licensing strategies, required training and technical support. A benchmark study comparing the options that successfully implement the CSR-H rules against these criteria would be an interesting future challenge.

As highlighted at the beginning of this chapter, no tests or benchmarks have been performed with the analyzed tools; therefore, a comparison among software functionalities able to identify the real capacities cannot be provided. As a conclusion to this section, considerations about general aspects and the overall philosophy are presented, leaving detailed analysis to future investigations. It is clear, however, that the trends highlighted in Section 5.1–increased use of 3-D FEA, on-line collaboration and extension of data/model use throughout the vessel's life–is common to almost all major classification societies in terms of services offered.

The 2-D section analysis and scantling definition according to rules still maintain their importance in the pre-contractual and first design stages. Tools-based databases are very useful in a design phase in which main design variable definition is in progress. However, standalone applications dedicated to particular purposes allow users to obtain results very quickly imputing only a smaller set of strictly relevant data.

Regarding 3-D FEM, while the standard approach is for the design tools to use an external solver for calculations, different approaches have been found in modeling and post-processing functions. For example, in a scenario in which most of the tools are standalone applications, some consideration about the choice to develop an application as customization of a general FEM tool may be a suitable approach. It has to be considered that 3-D FEM models are often used by designers for internal check and analysis (e.g. normal modes analysis, vibrations) with commercial FEM tools since they are not adequately supported by classification societies' software. Developing class societies' tools as customization of commercial ones, may appear to be a constraint to users in the choice of commercial FEM tool, but it extends the possibility of integrating commercial software capabilities and reducing the problem of data transfer. Importing and exporting data capabilities and implementation may not be always optimal solutions, in particular if the design process requires interactive changes. However, for less complex vessels, the availability of a toll with specialized features for modeling typical structures without involving data importing from external software and consequence training may remain the quickest solution.

Dynamic loading approaches and spectral fatigue analysis are probably the biggest innovations introduced in tools since the last committee review. This is clearly an attempt to go beyond the rules checking by providing instruments to fit the design goals, rather than simple approval. In this field, interaction between structural and hydrodynamics software is probably the most critical aspect. Automatization of loads transfer and implementation of statistical criteria simplify users' work, but it may reduce control of the calculation process and relevant results if a proper training for users is not foreseen.

During the software review, some information about optimization capabilities has been gathered. The thorough evaluation of this strategy would require a careful analysis and tests that are not subject of this chapter due to the limited resources available. A large potential of growth in this area may be found, considering that rule requirements are already implemented and so are available as constraints.

The increasing number of tools offering support to phases of a ship's lifecycle, other than only design, is interesting, in particular, hull monitoring and maintenance, which introduce the structure reassessment based on measurements of actual plating thickness performed by surveyors.

Class societies' PLM databases for new buildings and existing ships appear to have very similar functionalities. Main differences may be found in the possibility of interaction between class societies and other users (in some cases, external users may only access the information) and in the way the information is stored. Today, storage capabilities or data accessibility can be simply ensured, but the focus still remains on the quality of information and the related possibility of a quick use them. The risk is to save a great amount of files containing drawings, reports, certificates, and measurements, so that even if properly organized, it may become difficult to use, particularly for emergency support. Solutions based on 3-D models as a platform for most important data storage may be a way to supersede these mentioned problems, especially if interaction with stability and structural models is foreseen. Obviously, in that way, class societies' role of guarantor of design intellectual property rights rises to a higher level.

In this chapter, ten classification societies have been considered, and capabilities of approximately eighty types of software tools and applications have been briefly described. Despite all that has been discussed, this chapter represents only a part of what the class societies' software has to offer, and further study of these tools is highly warranted.

6. STRUCTURAL LIFECYCLE MANAGEMENT

6.1 Introduction

This chapter illustrates the importance of structural lifecycle management, including lifecycle data management, Operation & Maintenance (O & M), and condition monitoring systems' influence on the design process and integrity of marine systems. Lifecycle data analysis can be used as a feedback loop for the design team to test and check their designs. It can also assist with the identification of the most common failures and their consequences for future designs. This chapter contains four major sections: Tool Development, Data Interchange and Standards, Integration with Repair, and Integration with Structural Health Monitoring Systems. All four sections contain widespread and relevant information on each topic from the latest research papers. At the end of each section, a critical review is performed, identifying potential gaps.

6.2 Tool development

Over the last few years, various maintenance methodologies and tools have been developed that assist the overall lifecycle structural management. These methodologies and tools help minimize the risk and maximize the availability of the systems. They also provide valuable feedback on system reliabilities for the design team. One type of this advanced smart maintenance system was developed by Lee et al. (2012b), which provides onsite engineering data to field engineers including 3-D CAD design information during the work process. Radio-frequency identification (RFID) technology is applied to derive exact information into the smart maintenance system where it has been incorporated into mobile devices. Subsequently, a framework was presented by Temple and Collette (2013b) to schedule maintenance cycles for naval vessels in order to minimize the lifetime costs of the structure.

Another maintenance strategy was introduced by Lazakis et al. (2012a), which is called Reliability and Criticality Based Maintenance (RCBM). This methodology was applied for creating optimum maintenance system on board a Diving Support Vessel (DSV). Reliability and critical analysis of the main systems of the vessel were the starting points of this approach. Propulsion, lifting, anchoring & hauling, and diving systems were the subsystems analyzed in this case study. Furthermore, by using the Dynamic Fault Tree Analysis (DFTA) tool and the Birnbaum (Bir), Criticality (Cri), and Fussell-Vesely (F-V) reliability importance measures, the results of the above analysis have been validated. This created valuable information regarding component behaviors to be added into the lifecycle data management for the design process.

A paper by Ruede et al. (2012) also practiced a semi-automatic Fault Tree (FT) synthesis method but in conjunction with an innovative tool called “Hierarchically Performed Hazard Origin & Propagation Studies” (HiP-HOPS), which expanded to use the simulation platform SimulationX. This approach has the benefit of implementing a system model for the double purpose of behavioral simulation and reliability analysis. Additionally, the method features automation and simplification of reliability and availability prediction. This provides further advantages of enhancing speed and efficiency of the design modifications without any requirement for updating simulation and reliability models separately. As a result, it simplifies iteration of the design process in complex systems.

Schleder et al. (2012) presented an application of Bayesian Network (BN) to analyze different event scenarios using the parent marginal probability distribution of each component. This required computation of the posterior joint probability distribution of component subsets and function of the set of all nodes. This model has been implemented on a Liquefied Natural Gas (LNG) Regasification System on a Floating Storage and Regasification Unit (FSRU). Gazis (2012) also investigated another type of probabilistic response analysis and reliability assessment on subsea free spanning pipeline systems. These systems were exposed to random, wave-induced hydrodynamic forces. Monte Carlo simulation methodology was the chosen analysis tool for demonstrating the advantages of integrating a reliability-based design.

Multi Attribute Decision Making (MADM) methodology was described by Lazakis et al. (2012b) for selection and design of the optimum maintenance strategy for a given system. The TOPSIS ranking tool was used in combination with the rating and aggregation for converting unclear verbal terms from experts into more practical values. Markov Decision Process (MDP) is another Decision Support System (DSS) tool that achieves optimum design and maintenance strategy for time-dependent environmental agreement by using a consecutive decision-making frame work. A non-stationary MDP system, developed by Niese and Singer (2013), considers ballast water exchange and treatment policy changes. Therefore, MDP to model lifecycle decisions on this research determines the summary of the initial approach, outcomes, and conclusions resulting from the implementation of the mentioned framework.

The implementation of lifecycle assessment (LCA) and lifecycle costing (LCC) in marine systems design is proven. Aspen et al. (2012) have adopted this methodology in their work and discuss the future opportunities overcoming the difficulties facing it. The environmental effect from shipping is becoming an important factor for stakeholders in the maritime industry. Therefore, a holistic approach has been developed by Fet et al. (2013) that compares existing environmental assessment tools and introduces systems engineering as an approach to lifecycle designs. ABB has also prepared an insight into holistic performance management and optimization of any vessel type by recognizing energy efficiency, availability, and safety of the vessel (Ignatius et al., 2013).

Embrey (2012) examined the effect of human activities on errors in operations or maintenance on major marine accidents. Consequently, a novel regime was executed in an organized manner with a specific requirement regarding human caused risks. This resulted in the creation of a set of guidelines for addressing regulatory requirements for safety critical maintenance activities in the marine sector. Another safety related study was performed by New (2012) on the policy for Reliability Centred Maintenance (RCM) in the Royal Navy fleet. This study illustrates the engagement technique of RCM into the Safety Case regime of the First Sea Lord's Safety Argument of the UK Royal Navy rules. It supplies an integrated approach to safety and maintenance management. It also debates the potential paybacks of RCM by addressing deficiencies.

Tanizawa et al. (2012) proposed a new experimental methodology for self-propulsion testing of a marine diesel engine simulator in waves on a model ship. A marine diesel engine simulation program in this study provided a real-time control system of propeller rotating speed, imitating the characteristics of a marine diesel engine.

Reliability analysis in the marine industry can be also regulated and computerized. Hence, Linton (2011) created a management system for the RCM program of the Coast Guard surface fleet. This provides the standards and abilities desirable for the development of preventive maintenance systems that satisfy operational RCM requirements and standards called SAE JA-1011. Another study by Tiusanen et al. (2012) researches the application of management of Reliability, Availability, Maintainability, and Safety issues (RAMS) on offshore wind farms in the initial stage of turbine design. This paper presented guidelines for comparison of critical components on different offshore assets based on system availability and safety. Classification and evaluation criteria for different RAMS+I (Reliability, Availability, Maintainability, Safety, and Inspectability) factors are outlined and discussed as well. Additionally, Brown (2012) introduced overall life Reliability and Maintainability (R & M) management and assessment for defense programs. Capability and cost drivers are the major aspects of this study. It also discusses the management of R & M in topics of derivation of requirements, use of modelling, conduct of R&M audits, failure reporting, analysis and corrective action system (FRACAS), reliability demonstration testing, R & M risk management, and the R & M and dependability case. The dependability case itself identifies the sub-systems that have low reliability and are more prone to failures.

The use of decision making tools for repair planning was considered by Niese and Singer (2013). In this regard, the optimal maintenance strategy for time-dependent environmental agreement has been considered with regards to the implementation of the chronological decision-making framework MDP for ballast water exchange and treatment policy changes.

All of the above research papers present the development of tools by incorporating lifecycle analysis and maintenance in order to maximize efficiency of the overall system and minimize risks, thus ensuring safe system operation. These improvements can consequently be used as feedback for further enhancing system performance from the initial design stage. This means that invaluable information learned from failure modes, causes, and consequences can provide insight into the behavior of different systems and their components. In this respect, various tools are presented, which are also related to maintenance methodologies, such as RCBM, assisting in overall maintenance methodology development and lifecycle analysis. A major part of the complementary tools presented above is related to reliability analysis tools such as DFTA and BN. These reliability tools provide fundamental information and an analysis platform for measuring system behaviors and availability. Another important aspect is related to methodologies on the implementation of DSS. Two major types of DSS presented in this section are MADM and MDP. Both reliability and DSS tools specify the overall system performance and highlight the challenging areas related to the application in the lifecycle data management stage.

Moreover, this section also shows that there is continuous development in reliability-based approaches for marine applications including tools such as RCM and RAMS methods. A number of case studies have been identified, which are used for validating and testing the applicability of such approaches. However, the review of the existing research and applications so far has revealed potential gaps that can be tackled through future research. One of these gaps is related to the incorporation of condition monitoring systems within reliability and criticality analysis tools to obtain up-to-date and real-time results for decision making. Another gap identified through the examination of different methodologies is related to the enhancement of the relationship between business aspects with risk and safety. In this respect, the financial resources, the level of risk and safety should be considered in a combined way in order to achieve a more accurate representation of the overall system lifecycle. Another noticeable issue is the emerging combination of various maintenance tools into hybrid tools and methodologies that can be used on lifecycle data analysis and management. A good example is presented through the potential combination of DFTA and dynamic Bayesian networks (DBN). In this case, although DFTA is a widely applied tool on systems with large number of components, DBN can demonstrate the inter-component effects and inter-connectivity more efficiently while also considering the time variance effect among different system components.

6.3 Data interchange and standards

As many players are involved in the lifecycle management of marine structures, efficient data exchange between parties is a perquisite for successful lifecycle management. Foremost, it is beneficial to have a data exchange system between the design office and the Operation & Maintenance (O & M) team. This provides useful complementary information for future designs. In the recent decade, relays, push buttons, and light-bulbs have been replaced by processors, graphical user interfaces, keyboards, and track balls. Therefore, high-level computer languages like C++ and JAVA are becoming standard in the marine industry. As a result, this section illustrates all the data interchange forms and standards, which make it possible to maintain electronic copies of vessels' history throughout its service life in a centralized electronic location. Thus, Scherer and Cohen (2011) have discussed the Naval Surface Warfare Center Ship Systems Engineering Station (NAVSSES) as a center for collecting and managing machinery system data. Siemens Industry has also created software using their own light-weight 3-D neutral format JT for shipbuilding (Malay, 2012). This uses Visualization & Digital Mock-Up (DMU), Documentation & Archiving, and Data Exchange. JT format can facilitate data exchange among all stakeholders in a shipbuilding project. This can be implemented for Product Lifecycle Management by providing a shared platform for efficiently saving, representing, organizing, recovering, and recycling product-related lifecycle information.

Bureau Veritas (BV) developed a Lifecycle Management (LCM) system that uses some of its own in-house tools such as the VeriSTAR-HLC, VeriSTAR-AIMS, VeriSTAR-Hull, and Hydrostar modules (Renard, 2012). Using this system, shipyards are able to recall the drawings, technical notes, and computerized models of ships, as delivered, in an electronic Ship Construction File (SCF). SCF would also contain a structural 3-D model to be used by ship owners for classification societies and thickness measurement companies.

Tetrault (2012) presented the remote monitoring of engine rooms in marine industry. He highlighted that remote monitoring is well developed in land based power production systems, but the approach for the marine industry is not as simple. Thus, the offshore wind industry can be used as a starting point for developing such a system for the marine industry. A paper by Goni and Jambrina (2013) discusses the CAD design language implemented in ship design concepts by using three-level software architecture. The development framework has been considered in Windows 8 by using web applications, such as HTML5, CSS3, and JavaScript, and other native applications using C/C++. NET applications can be also developed using C#, VB, and F# programming languages. The user interface and experience for non-web application is described with XAML and the 3-D API for games and design applications is called DirectX.

In this case, the project by INCASS (2014c) focused on using different database standards for marine and shipping fields. One of the database standards defined in this project is called ISO 10303-11, which uses EXPRESS data format on XML schema to define its data structure. Another standard explained in this project is the Hull Condition Monitoring (HCM) 2.0 standard which focuses on data import strategy. This includes what type of data from structural analysis is recorded in the database. Their overall database model has two major sections, machinery and structural, with Java APIs to connect it to other analysis methods such as a structural reliability analysis tool. Stone (2012) described how Maritime Training Systems (MTS) achieved success on a Contracting for Availability (CFA) framework, which means it keeps a system in the agreed condition. This can be achieved getting both contracting parties to agree to the processes and methods to be implemented, which enable the Key Performance Indicators (KPI) to be assessed. He also reflected his concerns for gaining decent quality data to support the CFA initiative. A web-enabled tool called RAMtr@ck was adopted for application on MTS. This supplied user-friendly, semi-automated data collection and analysis tools for instantaneous response of utilization and availability of the system.

Standards are important in every stage of a vessel's lifecycle. That is why Shin et al. (2012) developed a prototype of a ship basic planning system based on the advanced IT systems for small and medium sized shipyards. For this analysis, a standardized development environment and tools were selected. These tools were used in system development for increasing competitiveness of small and medium sized shipyards in the 21st century industrial environment. Thomson and Renard (2013) expressed the importance of ship design standards in their research. Incorporating advanced information management technologies, they studied the 3-D models of the as-built assets. They also delivered an inclusive indication of challenges, solutions, and most suitable practice in the handover from shipbuilder to operator of a complete digital information asset. Finally, a paper from Mebane et al. (2011) discussed the variations of a government-led design on design approach, including schedule, organization structure, and design methodology. A new technique, called Set Based Design (SBD), has been added for assessing various systems and ship alternatives, although formal links to lifecycle management remain to be explored in this framework.

Hifi and Barltrop (2013) used a central database platform for forecasting structural defects. This platform assisted in the development of a reliability model that can consider individual components. However, this provided an insufficient representation of the overall reliability of the ship. Therefore, a method to adjust the reliability models using the data from experience-based methods was moreover produced. Thus, the critical structural details have been used by the inspection companies, class surveyors, ship managers, and ship designers for the calibration of the inspection planning for the decision support tool.

For regulating structural elements of the vessels and marine structures, it is important to have both safety policies and decision systems in place. Consequently, Forbes et al. (2012) have demonstrated an end to end safety argument for the fleet of Royal Navy. This safety policy is a Joint Service Publication 430, which applies to all Ministry of Defense maritime activity. This paper also considers the knowledge achieved from the loss of the Nimrod XV230 case study for endorsing the recent development and implementation of the Navy Safety Improvement Plan. Another study by Ostuni et al. (2013) looked into the application of DSS in structural analysis management and their application in shipboard security for supporting crew members in the effective conduct in failure events. This is a knowledge-based DSS integrated within a Damage Control System (DCS) for navies.

Summarizing the above, there are various formats that can be used for data interchange. One of the major issues is related to coding and system compatibility because software used in one system may not be applicable in another platform. This can be solved either by standardization or by creating plug-in programs. However, creating plug-ins for each program could be both challenging as well as relatively time consuming. This raises the importance of standardization of data formats. Standardized data formats can be used to store useful system O & M information as well. As a result, the design team can use the information created to identify the critical system areas that need further improvement. Another, important issue with data exchange models is storage of confidential data. Most companies would not like their data to be obtained by their competitors, and some of the data exchange models may not provide substantial protection from information piracy. However, it is useful to enable the sharing of data sources from various industrial organizations in one place in order to enhance the overall performance and safety of the marine sector. Consequently, it is vital to find a system that can both save enough data to achieve the previous goal without compromising confidential product information from different companies.

6.4 Integration with repair

Design processes may specify repair strategies and their integration with the overall lifecycle of the system. One of the most important areas in repair integration with maintenance is the inventory planning and organization. A paper by (Lutjen and Karimi, 2012) presented an optimized inventory system simulation approach for a single-echelon used in offshore wind turbine installations. For this purpose, they performed a heuristic reactive scheduling for synchronizing the installation vessels in different weather conditions in supporting the planning of offshore logistics systems. In this case, for logistics in marine environment, it is important to have a decent data gathering of the environmental conditions and degradation processes.

In this case, in a study by Lee et al. (2012c), a Multiplicative Decomposition (MD) method was used to achieve optimal results for a test miner tracked vehicle, considering noise variables in the Korea Deep Ocean Study (KODOS) area of the north-eastern equatorial Pacific. MD precisely determined the responses variance caused by deep-sea environmental variables. This information was then used in the optimization of the test miner tracked vehicle for deep-sea manganese modules collection. A project by INCASS (2014b) has also been working on creating a overall system for condition monitoring and a historical data gathering system that connects repairs, maintenance, and operational results to the design parameters of three different types of merchant vessels (container ships, oil tankers, bulk carriers). This could identify problematic areas and consequences of these failures to the overall performance of the vessels based on the particular design parameters.

Outfitting and replacement are other important factors in repair planning in maintenance. A study by Ruy et al. (2012) confirms that. This study is based on a scenario related to an outfitting division while not having any direct expertise to oversee the structural panel conditions on the installation of holes for the outfitting equipment. A challenging part of the overall outfitting equipment installation is related to the determination of the position and types of holes needed for a particular panel as well as the location of the interconnected silhouette of panels. As a result, most of these processes require an effective, but time-consuming, communication and discussion between the divisions, specifically hull experts and retrofitting experts. Therefore, this paper presented an automated hole-plan handling system for decreasing time wastage. Environmental conditions are also important in organizing a repair schedule, as harsh environmental conditions can cause difficulties in personnel and inventory transport and outdoor repairs. This harsh environment repair scheduling has been studied by Berg et al. (2012) where they looked into subsea repairs in the eastern part of the Barents Sea with harsh environmental conditions and seasonal ice. They suggested that during the harsh weather, an all-year Construction and Intervention Vessel (CIV) must be used in conjunction with ice management vessels.

Reliability analysis of components and structures during the operation also provides useful information regarding the lifecycle analysis of marine structures for the design team. For example, Wilkman et al. (2012) introduced structural analysis measurements of Aker Arctic. Data was gathered from 95 different vessels that were tested on 140 occasions. More specialized structural and data analysis tools were also developed in industry such as a simplified fatigue assessment rooted in beam theory with a spectral-based fatigue analysis procedure in MAESTRO introduced by Hunter et al. (2013). This method can generally screen for fatigue damage on vessel's hull. The MAESTRO software presented in this paper is open framework, and it helps by implementing a fully functional lifecycle framework for maintenance, monitoring, and reliability of ship structures.

A study by Dlugokecki and Hepinstall (2014) focuses on the Design for Production (DFP) concept and its integration with other concepts such as Design for Maintenance. This research emphasizes the fact that the design stage maintainibility of the vessel and ease of repair should be considered in order to decrease the operational costs of the ship's lifecycle. This should also include lowering the number of components and minimizing akward repair areas.

Overall lifecycle structural management can be integrated with repair in order to provide advantageous information on most common failure areas and their consequences to the design team. Additionally, it can also represent further information on any difficulties faced by the ship on-board crew during repair jobs. This information can be in the form of service cost, overhaul time, and unwanted failures caused by the repair process. Thus, the design team can use the information for suggesting additional measures in terms of maintainability aspects and timely decision making in order to overcome these issues. However, the type of information and data to be stored regarding repairs need to be further scrutinized. This would also require further research on tools and methodologies in order to connect the marine operational team with the design team. In some cases, this connection is rather difficult as challenges may arise, such as in the case of sharing information between the marine lifecycle management team and the design team.

6.5 Integration with structural health monitoring systems

Condition and health monitoring of the structural components is one the most important aspects of evaluating the lifecycle of a vessel. An initial study presenting the integration of a structural health monitoring with maintenance was performed by Ferrese et al. (2011). In this study, a particle swarm optimization algorithm was applied to obtain an ideal control for a desired eigenstructure. Nonlinear power system modeling has been used to establish an algorithm to be highly effective in the maintenance of the system output related to the specified eigenstructure, which provides the importance of structural integrity in planning. As a result, Caldwell (2012) illustrated the hull integrity management of Floating Offshore Installation (FOI) as well as techniques used to monitor this structural aspect regarding class requirements for the hull structure. One of the major methods of hull inspection methodology for vessels is dry-docking, but FPSOs cannot be dry-docked. Therefore, structural integrity management has been chosen to develop innovative techniques to support risk-based inspection of FPSOs without the need for the time-consuming dry-docking. Complimentary to the above, a study by Kvarme et al. (2012) demonstrated the structural integrity assessment being implemented for investigating the integrity of pipelines based on information from external structural inspections.

McCarthy and Buttle (2012) discussed failures in the tensile armor wires of flexible risers. This was detected through the reduction in applied stress in failed wires. A magnetic system was also introduced for measuring the stress in all the tensile armor wires for determining failures due to cyclic fatigue. A ship fatigue routing procedure was also investigated in a report by Mao et al. (2012) via a simple spectral method in long-term fatigue assessment of container vessels. The advantage of applying this method has been investigated on a container ship, which was proven that the fatigue life can be increased by at least 50% using an optimal ship routing system.

Stress/strain and ultimate strength are other factors that must be considered for structural analysis of the maintenance planning and lifecycle management. Subsequently, a paper by DuToit et al. (2012) introduces an advanced method of monitoring the stress/strain of power umbilicals. Fiber optic strain and temperature sensors were installed for this study. Distributed temperature and strain measurements were examined for manufacturing, verification, and continuous integrity monitoring. Ultimate longitudinal strength of hull girder was also investigated in a study by Nam and Choung (2012), which delivered an estimation of a Very Large Crude Carrier's (VLCC) probabilistic damage, magnified due to collision and grounding accidents based on Goal Based Standards (GBS) of International Maritime Organization (2003). The extent of the damage, expressed as a function of the ultimate strength, has been calculated using probability density functions with non-dimensional damage variables via the in-house software Ultimate Moment Analysis of Damaged Ships (UMADS), which uses the progressive collapse method.

Longitudinal bending of the progressive collapse behavior of the ship's hull girder was considered by Alie and Fujikubo (2012) who used an incremental formula based on Smith's method. Then, a case study was performed using this method on residual strength analysis of bulk carriers and a tanker with collision damages. Focus area of analysis has been on the effect of the rotation of neutral axial on the residual hull girder strength in the case of biaxial bending. INCASS (2014a) has created an innovative method of using strain gauges to obtain periodic loading conditions on structural elements of a vessel. These data are fed into an innovative inverse Finite Element Analysis (iFEM) where hydrodynamic and overall structural reliability of the system are modeled. Subsequently, these results are used for validation of the hydrodynamic calculations, reliability analysis, and FEM of the initial design predictions.

Another important area of stress/strain analysis of ship hull structure is the strength of welds. This has been highlighted in a paper by Piovesan et al. (2012), which discusses, compares, and optimizes the plastic constraint loss between Single Edge Notch Bending (SENB) and Single Edge Notch Tension (SENT) specimens for base plate and weld joints. This required a correction factor generated using corresponding Crack Tip Opening Displacement (CTOD) ratio β by the critical Weibull stress criterion. This was also defined by the internal stress distribution in plate thickness, considering critical fracture volume along the crack tip.

Corrosion is one of the most vital phenomena that have been taken into account in structural analysis in the marine environment. Thus, Htun et al. (2013) researched random field models for demonstration of corroded surfaces. The surface geometry of corroded plates has been considered using an innovative random field model called the Kerhunen-Loeve Expansion method. This is an alternative methodology to more common uniform corrosion models. Another study on corrosion was based on the impact of bacterial activity (Comanescu et al., 2012). This study was performed in the pipeline systems of the oil and gas transport systems. The corrosion lifecycle has been modeled as a function of Microbiologically Influenced Corrosion (MIC) risk with influence from water quality and bacterial population and types.

As mentioned previously, water quality is a critical factor in corrosion analysis. As a result, Gentile et al. (2012) studied water quality and material property effects of the Baltic environment on the quality of the steel material based on the ISO15156 Ed. Concentration of H_2S and pH have been used for the safety criteria of the Baltic environment. In general, both corrosion and fatigue can cause crack growth in hull structure. Therefore, Volling et al. (2012) have debated about ductile fracture arrest in line pipes. Subsequently, they have created an innovative approach on crack-arrest prediction using both analytical and numerical approaches. For the analytical approach, energy based criteria were used to capture pressure projections on material toughness values. In contrast, the numerical approach was used to demonstrate material resistance by energy based cohesive zone model on material damage created via Finite Element Analysis (FEM).

Lifecycle analysis is another criteria on ship structural monitoring and management which was evaluated on a study by Ohba et al. (2013). This study considers sustainability assessment vessel structure on risk of accidents based on environmental, economical, and societal factors. As a result, lifecycle structural optimization of the midship section of a double hull tanker was carried out in this work. Five optimization problems were evaluated: minimization of construction cost, optimization of Lifecycle Benefit (LCB) based on the oil outflow hazard, maximization of LCB considering the CO_2 emissions hazard, expansion of LCB considering the risk of failure, and optimization of LCB considering all the risk factors called the holistic risk.

The final important subjects to be considered for this study were the structural monitoring and testing methodologies and tools. One example of these type of tools is illustrated by Grasso et al. (2011). The paper presents the design of two hull monitoring system prototypes using temperature compensated laser based optical sensors to be installed on a double sided bulk carrier and an ice class tug boat. This required finite element analysis on defining the optimum sensor's installation areas on vessel's hull. Another monitoring tool, developed by Todorov et al. (2012), was called the Automated Ultrasonic Testing (AUT) data processing technique. This uses computer simulation for enhancing defect detection and mitigating the inspection actions. Probability of Detection (POD) and accuracy of defect sizing was determined for six illustrative AUT systems with demonstrative girth weld embedded defects. Quantification methodology guidance was built, and measures to improve the performance AUT was then assessed by a built-in quantification methodology.

In summary, this section provides extensive background research on different structural health monitoring and analysis systems that can assist in optimizing structural integrity. The above review includes various fatigue and stress analysis models developed in different sectors while also referring to different structural monitoring and detection systems. Moreover it highlights the importance of integrating FEM results with lifecycle analysis for the design team. However, a study on the usefulness of different monitoring and detection equipment on FEM results of the marine structures would be beneficial to include in future work. Another interesting area that has been highlighted in this section relates to the analysis of collision damage in the structural integrity of vessels, although further work is needed in order to suggest additional recommendations to the design team on minimizing structural damage and optimizing structural integrity related to collision accidents. Finally, this section examines studies on the effects of corrosion on structural integrity. Ship design needs to further consider mitigation measures including coatings; therefore, a study on the behavior of coatings, paints, and anti-fouling systems could prove crucial.

6.6 Summary of the lifecycle structural management systems

In summary, this chapter has looked into the relationship between LCM tools, data interchange and standards, integration of structural health monitoring systems, structural repairs, and analysis with the design process in marine structures. It has demonstrated that valuable information obtained from maintenance, repairs, and structural analysis can be used to identify weak points in designs and furthermore, suggest additional improvements. It is useful to consider that the design team needs to further incorporate the ease of repairs and maintenance in ship design in order to increase maintainability and address extensive operational expenses. In brief, it is vital to have an integrated lifecycle system that connects the overall design process with other operational parameters such as repairs and maintenance.

However, there are challenges that need to be considered in the development of lifecycle data management for ship design. One of the major tasks is the application of such methodology on a full ship/marine environment. As no full-scale trial of such a system has been made yet, an accurate assessment of the increased performance and benefits for the vessel's structure of this methodology is not currently possible. Additionally, the studies that consider areas of LCM do not incorporate all its phases including the combination of novel research with industrial applications for design, survey, inspection scheduling, maintenance, and repairs. Another issue is the defragmentation of different, existing, and upcoming lifecycle management platforms, databases, and tools inside a common framework and working platform. This could result in incompatibility between different platforms, which may cause difficulties in sharing information.

Moreover, potential gaps have been identified in terms of interconnectivity of tools that may assist in the prioritization of maintenance and repairs such as the combination of DFTA and Dynamic Bayesian Network (DBN). The above may consider the time-dependent degradation of structural elements which can be modeled accordingly. Additional consideration regarding the standardization of DSS would be also beneficial. Moreover, most maintenance methodologies either consider operational or business aspects with no integration between two major features of achieving effective maintenance regime.

No data storage security standard is fully addressed, especially when considering the confidential manner and sensitivity of shipping data. Accordingly, a central database that can be used across the marine industry by operators and other stakeholders would be essential in order to enhance performance, safety, and environmental credentials of the sector. However, this cannot be achieved without a safe and confidential information sharing protocol. Moreover, the type of the data to be saved is important such as maintenance intervals, repair reports, and structural condition monitoring data. This would require more comparative research on different structural monitoring and analysis tools. Finally, a comprehensive study on using more automated systems could be beneficial in reducing the overall cost and accelerate the overall analysis process in structural monitoring systems.

7. OBSTACLES, CHALLENGES, AND FUTURE DEVELOPMENTS

Throughout this report, several recurring themes emerge that contain either foci of ongoing research or a notable gap between the industry's desired capability and the current state of the art. Several of these themes have elements present in both the research foci and the gap categories, indicating areas worthy of further analysis and discussion to identify higher-level obstacles, challenges, or future development needs. Four main themes are identified here to structure this discussion: increased lifecycle considerations in structural design, the continued focus on risk- and goal-based design approaches, the rapid growth in numerical models available to the designer, and the increasingly-important role played by classification society software.

Perhaps one of the largest themes revealed by this committee's work is that of increased consideration of the structure's entire lifecycle. At the design stage, interest in better understanding the overall lifecycle has resulted in new approaches to directly simulate or optimize repair and maintenance strategies during initial structural design. Such approaches range from formal optimization using detailed through-life simulations to more higher-level commentary on the trade space between design-for-production and design-for-maintenance under the aegis of design-for-X. Additionally, scenario-based design methods, such as epoch-era analysis, are growing in popularity for the general marine platform design problem. Such specific scenario-based analysis further opens the door to consider specific repair and maintenance impacts on a vessel's earning potential and safety through-life. At the current time, most of the approaches reviewed were in the early stages of adoption and development, with the origin of the developments resting primarily in academic-only or academic-industry joint projects. Also currently, there appears to be a gap between the theory and the practical state of the art available for vessel designers. For specific analysis types, such as LCA and LCC, industry-standard frameworks and common databases required for practical analysis on individual projects do not yet exist. The transition of these approaches to applied state of the art remains anticipated, not observed. However, given the success in using direct lifecycle simulation of hydrodynamic responses for operability, fuel economy, and comfort in the last decade, perhaps this transition is not far off for the structural domain.

The theme of increased consideration of the structure's entire lifecycle is present far beyond design stage activities. One manifestation is in the growing demand for through-life support of marine structural systems. There is long-standing interest in getting design-stage data readily available to support on-board inspection and updating, technologically, web-enabled storage, and portable viewing of this design data appears feasible today based on the references presented in this report. The committee's work revealed that almost all major design software vendors now offer in their design suites some sort of PLM add-on that are configured to solve this problem. Likewise, all major classification societies are touting their through-life management software along with their initial design approval software. However, what is largely missing is an agreed intellectual property protection framework for the data within these systems. Shipyards are rightly concerned about exposing detailed production information to all downstream users. However, without an accurate as-built description of the structure, many through-life monitoring and updating techniques become impractical. Continued interest in the use this type of data for emergency responses after a collision, fire, or grounding is further driving efforts to arrive at a workable solution to this IP problem.

An area where technological challenges still remain is through-life structural health monitoring. Unlike rotating machinery, where clear systems have been developed to interpret real-time monitoring data, the structure community struggles with the data-to-decision problem. Current systems are able to record accelerations, strains, and displacements throughout the structure. Translating this data into improved operations and repair decisions remains difficult. Like many other fields, this represents a "big data" challenge. This is a field where several new systems were proposed during the time period of this committee's mandate, and future development in this area is anticipated.

The development of both risk-based design and goal-based standards has been chronicled by the ISSC over the past two decades, and it represents the second major theme for this chapter. These topics continue to generate new publications and approaches during the current ISSC period. While early efforts mainly focused on setting up the frameworks for these systems, the current publications are split between larger philosophical issues and the details of attempting to implement practical risk-based or goal-based design approaches. Overall, many rule sets are now moving toward a probabilistic foundation, and the explicit inclusion of uncertainty in design approaches is now commonplace. For example, as discussed in Chapter 4 of this report, risk and reliability measures are now often built into complex optimization and decision support systems. Setting safety as a design objective has been widely discussed in the past though only a few examples of multi-objective optimization frameworks for structural safety have been presented in the past. During this committee's mandate several papers have now shown Pareto fronts between safety and cost or weight of the resulting system. This indicates that such trade-space data can be developed in a practical manner today. However, the limits of these approaches are still not clear. While they have their origin in safety-related concerns, is it appropriate to establish risk and goals for other aspects of designs such as profitability, maintainability, or producibility? Example and complete systems to implement these approaches in ship and platform design are currently sparse; much like LCC and LCA models, the theory has been well established, but ready-made tools for practicing designers are still lacking.

The continued rapid growth in the types of numerical modeling required in new design projects is the third theme for this chapter. The types of models possible and the level of detail continue to grow, with new modeling frameworks proposed almost yearly. Selecting the correct level of detail to model the various aspects of each design is now an essential step in setting up a process to develop a new design. Within this committee's report, references note that the continued expansion of such modeling might be reaching a point of diminishing or negative returns in terms of making better design decisions.

Additionally, new tools were reported whose primary purpose was to implement simpler versions of complex calculations that were already available in their full form. The idea of these programs is that the modeling would be faster and less error-prone if the user had a more limited set of modeling options. The question of selecting the correct level of modeling detail for each design does not seem to have been formally addressed to date in the literature, nor has a systematic approach to validating such models been widely discussed. This is especially true if the number of structures designed to date by such novel models is limited. This problem is one of many hierarchal levels, as once a modeling approach is selected (e.g. FEA), the level of detail of that particular approach is normally adjustable by the designer.

A key component of managing the growth in numerical models is in efficient transfer of data among different modeling programs, or among a central design repository and each modeling program. Such data transfer has been a common theme of this committee's reports for many years, and continued progress can be seen in this area as well. While no major standard developments (e.g. STEP) were reported during the current committee's mandate, continued refinement of data exchange and numerous ad-hoc exchange approaches relying on application API and common data definition languages (e.g. XML) were reported. Given the rapid growth in the types of models available to the designer, the development of a universal file format or format converter is likely entirely improbable at this point in time. Thus, efficient one-off integration may become a topic of interest for integrating such toolsets.

The growth in modeling complexity and the sheer number of models have led to increased computational demands to complete design simulations. This is especially true when such models are tied into optimization frameworks. This committee performed a first review of parallel processing options for such frameworks and found wide availability and adoption of cluster-style computing today. Coupled with the growth of population-based optimization approaches, such computing resources now allow the designer to perform wide-ranging trade studies in a time efficient manner. There is growing interest in the use of GPUs to further accelerate such models; however, developments in this area are much more limited to date. Whether GPUs will be able to overcome the economies of scale now present in cluster-style computing is an interesting question for the next ISSC. The use of surrogate models to further reduce the computational burden of detailed numerical models was first discussed by this committee in 2012. In this committee's report, a more detailed overview was presented, along with some initial recommendations for modeling type. However, wide-scale application of surrogates in industrial optimization seems to be lacking at the moment, as the cited papers were almost universally academic in origin. At the current time, there appears to be little preventing the adoption of such models by industry, with extensive open-source toolkits available in popular languages such as MATLAB. If wider adoption of these models is not seen in the future, it may indicate that the time and uncertainty associated with building such a model does not make it cost competitive with the falling cost of direct simulation via clustered computational resources.

Finally, the growth in complexity of classification society software is the last major theme for this chapter. The updated review of the classification society software revealed in detail how complex these applications have become. Almost all societies now include links to advanced simulation such as spectral fatigue and through-life data access from their systems. Classification societies are well-positioned to support through-life data access, and as a disinterested third party, these may have a role to play in resolving the IP issues surrounding through-life data access. However, given the focused role of classification in safety certification, other elements, such as optimization for production cost or production detailing, are absent from such systems and unlikely to be added. This requires detailed design information to exist in (at least) two systems simultaneously. Thus, one key area where smooth data transfer is becoming increasingly important is between classification society software packages and external design-focused CAD packages. While the review of classification society offerings revealed that data exchange is important to all societies, this is an area where the industry would appreciate smoother data exchange. As class society software continues to grow in both complexity and importance to the structural design process, the role this software plays and the links between this software and the rest of the design environment is expected to become increasingly important.

8. CONCLUSION

Reviewing and analyzing the last three years of literature have revealed several constant themes in design methods. As discussed in Chapter Two, there is continued interest in risk-based design and uncertainty approaches in design. Additionally, the inclusion of various lifecycle events, from conventional lifecycle costing to more advanced, scenario-based design methods, remain a topic of interest to the marine structures community. However, the marine structures community is still not at the point where a single methodology dominates any of these discussions. Most of these trends are equally reflected in the design tools reviewed in Chapter Three. Again, a strong interest in higher fidelity and through-life models was observed, alongside the normal progress made in numerical methods and design software. Additionally, the problems of data exchange and lifecycle data management remain at the forefront in this community. The issues to be addressed continue to extend beyond technical data interface challenges, with unresolved IP issues and access controls high on the list of challenging problems that remain.

Optimization continues to attract significant interest. Indeed, the synthesis process required for a complex marine structural design is complicated enough that assistance from a computer is widely viewed as beneficial. Chapter Four reviewed numerical methods used for both optimization and enhancing optimization via techniques like surrogate modeling and GPU programming. However, that is potentially not the most exciting of the developments in this field. Instead, the ongoing work on transforming optimization into a design support methodology instead of an answer-giving black box is very notable. This marks the second Committee IV.2 report in a row in which extensive discussion of design frameworks and procedures for optimization has played a significant part in the discussion of optimization. Continued work on integrating optimization into the overall structural design methodology is expected.

Classification societies have unique roles in influencing the initial design of ship structures and managing them through-life. As tools influence the design process and methodology, this report reviewed classification society tools for structural design, analysis, approval, and through-life support. Comparing against an initial review from the year 2000, Chapter Five revealed not only the expected increase in modeling fidelity and automation but also detailed extensions into through-life data management by almost all classification societies. However, it is equally clear that much work remains to be done in ensuring smooth data transfer between such proprietary tools, other design tools, and data management systems.

Continuing on from the large LCM review in the preceding ISSC, this committee examined lifecycle modeling and data management in Chapter Six. It is clear that rapid progress is occurring in this area, with new tools appearing regularly and increased research intensity on the topic. This is especially true for design-stage prediction tools as well as tools that can integrate data from structural health monitoring systems. Equally exciting is the increased emphasis on integration of such approaches into decision making and repair. LCM is expected to receive intense research attention in the future. Finally, the Committee was able to extract some key themes and current gaps from the topics reviewed and present them in Chapter Seven. This review was highly encouraging. While it is clear that new tools and approaches are being developed constantly, it is equally clear that there is room for future generations of researchers to improve structural design methods to better suit the developing needs of industry.

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