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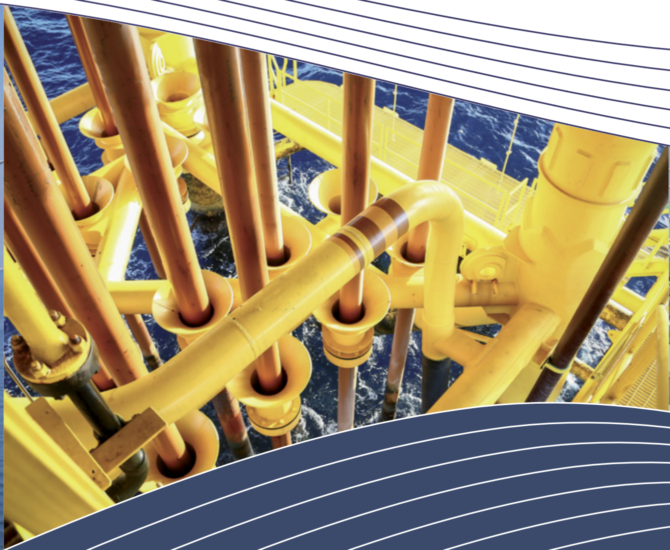
Technical Committee Reports



20th International Ship and Offshore Structures Congress
ISSC 2018
Liege – Belgium • Amsterdam – The Netherlands

Edited by
Mirek Kaminski and Philippe Rigo

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Volume 1

Technical Committee Reports

Edited by

Mirek L. Kaminski

Delft University of Technology, The Netherlands

and

Philippe Rigo

University of Liege, Belgium

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Preface

The first volume contains the eight Technical Committee reports presented and discussed at the 20th International Ship and Offshore Structures Congress (ISSC 2018) in Liege (Belgium) and Amsterdam (The Netherlands), 9–14 September 2018, and the second volume contains the reports of the eight Specialist Committees. The Official discusser's reports, all floor discussions together with the replies by the committees, will be published after the Congress in electronic form.

The Standing Committee of the 20th International Ship and Offshore Structures Congress comprises:

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On behalf of the Standing Committee, we would like to thank the sponsors of ISSC 2018.

Mirek Kaminski
Chairman

Philippe Rigo
Co-chairman

Delft, 1st May 2018

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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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M. Toyoda, *Japan*
J. Varela, *Portugal*

KEYWORDS

Design Methodology, Product Lifecycle Model, Optimization, Offshore structures, Classification Society software, Lifecycle Structural Management, CAD, Design Software

CONTENTS

1. INTRODUCTION

Design methods for ships and offshore structures and their integration with production, maintenance and repair continued to be an area of great interest and further development in the 20th ISSC Committee work. Together with updating the themes covered in the previous Committee work, the current Committee also expanded its remit with additional aspects of key interest. In this respect, Chapter 2 presents the work performed on design methods following the work of the preceding ISSC IV.2 Committee presenting either large activity or (arguably) great potential for improvement. This is related to the 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 particular, this aspect is oriented to the discovery/selection of the best match between the available synthesis methods and available/required structural analysis methods/tools.

Over the last few years, the development of the design tools for marine structures has been characterized by the extension of the software packages functionalities in order to create tools, which can be used from the early design phases of a new ship, throughout its entire life. These design tools address several aspects of the design of a ship, such as safety, hazard scenarios and risk assessment, life-cycle maintenance, accident scenarios, and optimization. The analysis of the state-of-the-art scientific literature has shown that integration of these functionalities in the design tools have led to two different approaches in the development of the tools: monolithic software and modular systems. The above is addressed in Chapter 3 together with the recent progress of Computer-Aided Design (CAD) packages for ship design, focusing on the new 3D capabilities of this software and on the impact that 3D design is having on the maritime industry.

Following the previous Committee's official discusser suggestion, the current Committee also included a chapter particularly related to offshore structures. In this respect, Chapter 4 addresses the developments within the offshore structures design methodology and the related design challenges, latest progress and trends. In addition to the above, a survey on offshore structures design software was conducted identifying the tools and software being used for the design of offshore structures and related activities (e.g. engineering, construction, etc.). The survey also depicted the usage of various tools employed by offshore vs. ship designers as well as trying to identify existing differences related to the main activity of the stakeholders and tool usage nuances associated with different offshore units/structure types.

Chapter 5 follows another aspect suggested by the previous Committee's official discusser; that is the presentation of the state-of-the-art vs. state-of-practice. This is a new theme into the ISSC IV.2 Committee's work in order to bridge the gap in between the research work presented within the Committee's remit and the practical applications that stem out of it. The above address one of the key ISSC Committees' tasks to identify knowledge resulting from research, which is novel, validated and is relevant to use by industry and regulatory bodies. In this respect, the adoption of a Theory to Practice Ready Papers (TPRP) approach is suggested by the current Committee for high quality and impact research work.

Chapter 6 presents the results of a benchmark study on the comparison of classification societies' software employing the most up-to-date IACS Common Structural Rules for double hull oil tankers. In this respect, an Aframax double hull tanker is analyzed using six specific classification societies' software tools.

Lifecycle management is a key feature from the initial stages of design up to the end of a ship's operating life and becomes an increasingly important issue in industry due to various reasons. Chapter seven addresses these issues and further developments both at operating and environmental point of view. Moreover, this chapter presents the data integration from early design to dismantling of the ship while the use of smart sensors as part of digitalization is also explored.

Finally, key obstacles, challenges and future developments, which will have an impact on the Committee's work, are also presented at the end of this report.

2. DESIGN METHODS

Following the work of the preceding ISSC IV.2 Committee that defines ship structural design methodology, the work of the current Committee focuses on both pf them. Each one presents either large activity or (arguably) great potential for improvement. The first aspect relates to the 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 other words, this aspect is oriented to the discovery/selection of the best match between the available synthesis methods and available/required structural analysis methods/tools. This aspect will be covered in subsection 2.1, titled Review of Design methods. The second aspect is related to Design for X, where "X" represents a specific goal such as operability, environment, safety, or production. It will be covered in subsection 2.2, titled Review of ship structural design for X. Several others "X" are also listed in the Chapter 6.

2.1 Design methods

Any methodology for the ship structural design needs to be part of the ship design methodology and as such it is under the time constraints relevant to the ship design process, which can range from several weeks to several months. At the same time, the used methodology needs to satisfy all the demands prescribed by the applicable rules e.g. new IACS Harmonized Common Structural Rules (HCSR) for bulkers and oil tankers. In such environment, it is evident that it is necessary to find the right balance between the characteristics of the design problem and available/applicable analysis and synthesis methods.

2.1.1 Optimization methods

According to Coello et al. (2007), general search and optimization techniques can be classified into three categories: deterministic, stochastic (random) and mathematical programming methods (Figure 1).

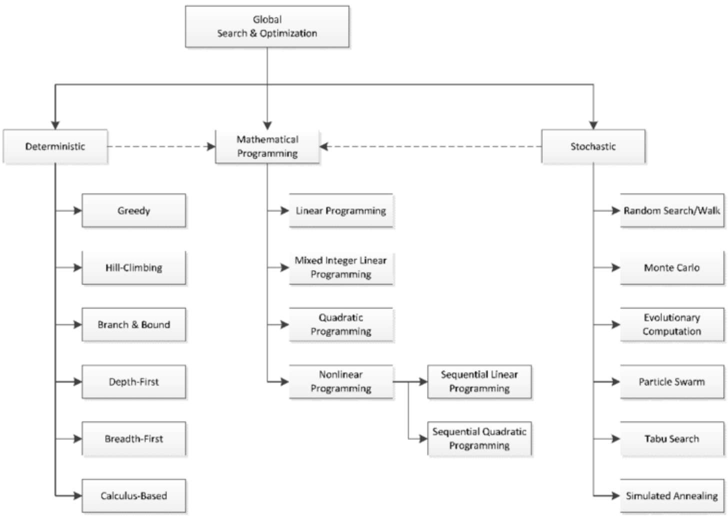

Figure 1: Classification of global search and optimization methods

In general, two types of optimization algorithms are of a special interest to ship structural design. The first ones are the generally applicable multi-objective optimization algorithms capable of obtaining the Pareto frontier that can provide the designers with the valuable insight into the trade-off between the improvement of one objective and deterioration of other objectives. The second ones comprise computationally efficient single objective optimization algorithms capable of exploiting the structural analysis tools characteristics. However, in order to enable ship structural optimization of a realistic global ship structure (full ship models or three hold models), it is still necessary to employ two separate options. One can use the tools based either on prescribed classification society rules, or to simplify the structural problem inside the optimization loops in order to reduce the number of degrees of freedom of the original/standard FEM model. Optimization approaches with FEM models are also used for dimensioning of realistic local structures such as for the hatch covers.

Romanoff et al. (2016) presents review of the development of an effective direct strength analysis approach utilizing homogenization, the finite element method, and optimization. Homogenization is used to transform the originally periodic, stiffened plate or web-frame structure to an equivalent single layer (ESL) plate or beam structure, respectively. This makes the finite element analysis (FEA) very fast and allows modeling of the stiffness and mass of the complex structure accurately. In most of the cases, classical first-order shear deformation theory (FSDT) is adequate, but new structural solutions require enhancement of the theory to account for the influence of strain gradients. The averaged response produced by FEA is transformed to periodic response to enable the prediction of spatially fluctuating stresses and first fiber estimate of the strength. The paper summarizes recent developments on the approach with respect to quasi-static and vibratory response, but also non-linear response such as post-buckling and tensile failure under multi-axial loading. It is emphasized that one of the main benefits of using ESL in ship structural design is that is allows meshing of the structures with different (optimal) mesh densities needed for different types of analyses. Using this approach Raikunen (2016) performed optimization of a passenger ferry using the ship global 3D FE-model and ESL approach. This structural analysis approach was coupled with particle swarm optimization (PSO) code capable of searching effectively global optimums. The ship was meshed for primary (σ1) level structural analysis using a coarser mesh, while the tertiary responses were analyzed by using sub-models at certain regions.

Um and Roh (2015) applied Sequential Quadratic Programming (SQP) and genetic algorithms to determine optimal principal dimensions of the hatch covers of a 180,000-ton bulk carrier. Some dimensions representing the shape of the hatch cover were selected as design variables and some design considerations related to the maximum stress, maximum deflection, and geometry of the hatch cover were selected as constraints. Minimization of the weight of the hatch cover was selected as an objective function. FEM model of hatch cover was made in ANSYS using only shell elements for modelling of plates, strong beams and stiffening. Single objective multi-start approach based on the combination of GA and SQP in the final phases of optimization was used to find global, not just local optimum.

Na and Karr (2016) proposed a Pareto Strategy (PS) multi-objective function method developed by considering the search direction based on Pareto optimal points, the step size, the convergence limit and random number generation. The success points between just before and current Pareto optimal points are considered. PS method can also apply to single objective function problems, and can consider discrete design variables, such as plate thickness, longitudinal space, web height and web space. The optimum design results are compared with existing Random Search (RS) multi-objective function method and Evolutionary Strategy (ES) multi-objective function method by performing the optimum designs of double bottom structure and double hull tanker which have discrete design values and using minimal dimension rules-based approach. Its effectiveness is shown by comparing the optimum results with those of RS method and ES method.

Vaucorbeil and Patron (2017) used genetic algorithms to optimize the design of the gun foundation of an Offshore Patrol Vessel. The methodology considers the main properties of materials and the loads acting on foundation, such as gun blast pressures, recoil force and dynamic inertial forces. Design constraints are related to the maximum allowable stresses, fatigue failure, and natural frequencies of the structure. The objective variable is to minimize the weight of the foundation by altering the thicknesses of metallic elements, while satisfying the design criteria of the classification societies. FEMs are used to determine the state of stress through static structural analysis, and the natural frequencies of the structure through modal analysis. The method is therefore based on a two-way coupling between the genetic algorithm-based optimizer and the finite element solver. The authors claim that its implementation provides potential to efficiently search for optimized designs, and that the optimization tool can be used to automate the structural design of any portion of the ship.

Garbatov and Georgiev (2017) also applied a multi-objective nonlinear optimization method to a stiffened plate, in this case subjected to combined stochastic compressive loads. A genetic algorithm with a termination criterion is employed, which considers the minimization of the weight and structural displacement, as a dual objective structural response. Instead of performing complex structural analysis, as the previous methods, this method resorts to a reliability analysis based on design constraints, which is incorporated into the optimization procedure. The reliability index is employed to identify the topology of the stiffened plate as a part of the Pareto frontier solution obtained as a result of the optimization algorithm.

2.1.2 Surrogate modelling and variable fidelity approaches

Surrogate / approximation / metamodeling process, is the key to surrogate assisted optimization. It can be stated that surrogate modeling actually evolves from classical Design of Experiments (DoE) theory, in which polynomial functions are used as response surfaces, or surrogate models. Steps necessary for the generation of surrogate models include planning of experiments or sampling, execution of simulations with original analysis methods, generation or creation of selected surrogate model and validation of surrogate model adequacy. However, there are a number of research studies, including some in the ship structural design field, which generate surrogate models suffering from accuracy.

Although often neglected or not taken with enough care, it is necessary to have a metric that will enable reliable selection of surrogate modelling technique to be used. In Jin et al. (2001) the authors have compared different techniques and suggested the next performance metrics for use:

- Accuracy – the capability of predicting the system response over the design space of interest.
- Robustness – the capability of achieving good accuracy for the 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.

Andrade et al. (2017) speculate that direct optimization routine on every single part of the hull is not feasible with today's numerical methods and probably, according to the Bremermann's limit, will never be possible. They propose parametric structural design as a promising alternative for hull design, capable of combining weight reduction, material efficiency and safety. The objective of the paper was to demonstrate the application of a design of experiments sensitivity study for a parametrically modelled global structure of a platform. The concept of the procedure was shown, through a simplistic design optimization of a mid-ship section subjected to bending moment, that it is possible to determine valid regressions for ships structural models at a conceptual level using DoE in combination with FEA.

Andric et al. (2017a), emphasize that for multi-deck ships with extensive superstructures (such as passenger ships, RoPax, etc.) the global structural response can be particularly complex.

Main global topological parameters (e.g. size of side openings, stiffness of longitudinal bulkheads, etc.) have dominant influence on the shape of hull girder stress distributions over the ship height. The paper also proposes uses of DoE techniques to systematically study the influence of multiple topological parameters on the global structural response obtained by FEM analysis. The paper demonstrates that use of simplified FEM on passenger ship and how different topological variants can lead to different optimal structural scantlings with regards to chosen design objectives (mass, VCG, etc.). As a second step, after selection of the preferred geometry/topology variant, the authors propose and demonstrate use of both multi objective (MOPSO) and single objective scantling optimization (SLP) using the same FEM model of selected topo/geo variant.

Ma et al. (2016), presented an approach, newly implemented in software MAESTRO, capable of optimizing realistic structures. It combines multi-objective GA local optimization of a part of structure with the same scantlings, called design cluster, with the optimization on the global level where global measures like vertical center of gravity can be used as objective. At global level, design variables are designs that are to be selected from a set of Pareto solutions of each design cluster. The approach has successfully been applied for midship and full ship FEA based optimization of a naval frigate.

The same optimization approach and tool (MAESTRO) is used in Kim and Paik (2017) where it was applied for a design of a VLCC-class double hull oil tanker. The paper is more focused on using the Paik's ultimate limit state library ALPS/ULSAP for evaluation of stiffened panels adequacy and ALPS/HULL for evaluation of hull girder ultimate strength. Neither loads nor adequacy are done according to current IACS CSR BC&OT, however the use of partial safety factors that could be used to accommodate results to some extent is mentioned. Kim and Paik (2017) also propose an optimization approach for the design of preliminary hull structural scantlings (see Figure 2) as an improvement to the current industry standard based on the manual scantlings remodeling/feasibility checks. However, the proposed procedure, does not include automatic implementation of loads defined by IACS CSR BC&OT Rules, nor check of feasibility by IACS CSR BC&OT adequacy criteria, which could present a problem for the use of the proposed procedure in industry for the design of merchant ships that need to satisfy IACS CSR BC&OT.

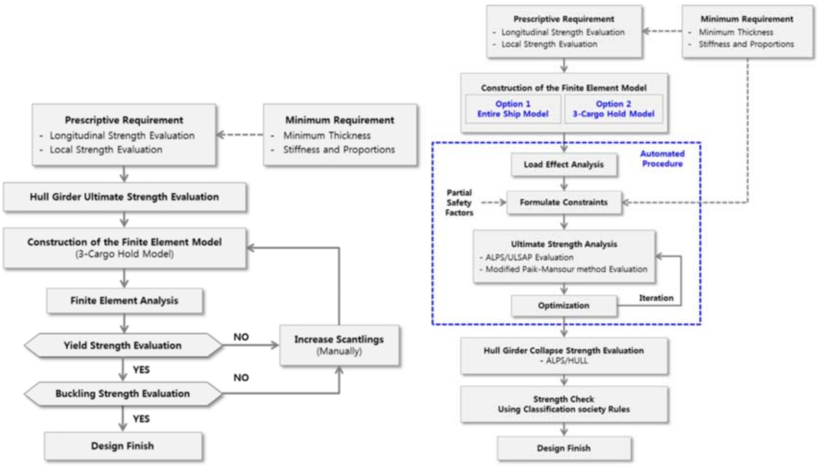

Figure 2: Approaches for the design of preliminary hull structural scantlings; a) Industry standard (IACS 2012) b) Optimization approach proposed by Kim & Paik (2017)

An optimization-based approach for the design of preliminary hull structural scantlings of ships classified by IACS CSR BC rules is further elaborated in Andric et al. (2016). The authors also specify the need for topology/geometry variants investigation using the same or simplified FE models. The proposed approach includes automatic FE model loading and feasibility checks using criteria prescribed by IACS Rules. The proposed design approach is applied on the industrial structural design of Handymax bulk carrier, made in close cooperation between ship owner team, shipyard team and university, using the in-house software OCTOPUS CSR coupled with MAESTRO. Optimization approach is very similar to the one given Ma et al. (2016), although single objective SLP algorithm was used on the optimization sub-problem/design cluster level.

Lee et al. (2015) proposed a design process composed of three parts: definition of geometry, generation of response surface, and optimization process. To reduce the time for performance analysis and minimize the prediction errors, the approximation model is generated using the Backpropagation Artificial Neural Network (BPANN) which is considered as a Neuro-Response Surface Method (NRSM). The optimization is done for the generated response surface by the non-dominated sorting genetic algorithm-II (NSGA-II). Through case studies of marine system and ship structure (substructure of floating offshore wind turbine considering hydrodynamic performance and bulk carrier bottom stiffened panels considering structure performance using NLFEA), the applicability of the proposed method for multi-objective side constraint optimization problems have been confirmed.

Knight (2017) presents a so called medium-fidelity approach which is in between the two main approaches normally taken for the early-stage structural design of multi-hulls: the high fidelity FEM of the ship from the very beginning, and the use of rules, class society guidelines and engineering safety factors. The approach consists in modelling the ship hull with complete subdivision using non-uniform rational basis splines (NURBS) surfaces and assumes that sectional loads are provided by hydrodynamics tools. The design of the structure is handled in two steps: (1) the convergence of the structural design, subjected to longitudinal load information, to maximize the objective functions; (2) the verification of the structural design subjected to longitudinal and transversal load information. In this case, physics-based solutions are applied for structural strength calculations.

2.1.3 Other relevant structural design approaches

Currently, the design methodology applied to ship structures is heavily supported and even based on digital simulations of common conditions and scenarios which occur during the ship's life-cycle. This trend becomes even wider with the continuous increasing of the computational power available, even for small to medium design offices and shipyards. New solutions for specific structural arrangements are digitally modelled and intensively tested and optimized in specialized simulation and optimization tools. Although the computational simulation and analysis of structures is already a common practice, the Classification Societies' (CS) rules are still fundamental on the design of marine structures. Since 2012 the IMO Goal Based Standards (GBS) were adopted and implemented by the SOLAS convention. Based on the GBS standards, IACS and their associated CS members developed the common structural rules, which dictate now the main guidelines for the structural design of bulk carriers and oil tankers, (Peschmann et al. (2017).

The Finite Element Method (FEM) has become one of the most common methods to analyse the effects of loads on ship structures and suggest corrections and/or improvements to the structure in early design phases. The large amount of research work during the latest years on ship structural design, which uses this methodology, reveals that the FEM will continue as one of the preferred methods to design and check ship structures in the next years. Among the most relevant and recent research works, demonstrating the importance of this method, are the ones published by Andric et al. (2017b), Joung et al. (2017a), and Cherian et al. (2017).

Andric et al. (2017b) presents an example of modern procedure in structural design of an "Open Type" livestock carrier. This type of ship represents a structural challenge due to the partial but effective participation of the superstructure both in the longitudinal and transverse/racking strength due to the absence of transverse bulkheads in the superstructure. The work highlights the required cooperation between construction yards, Classification Societies and faculty design teams as an example of modern procedure in rational structural design. They define three different design stages, in which FEMs become more complex and mature: (1) the Concept Design Phase (CDP) in which the Rule based tool is combined with generic FE model to ensure realistic calculation of primary stress distribution; (2) the Preliminary Design Phase (PDP) where only the full ship FEM model is capable of simulating realistic 3D effect of Hull/superstructure interaction without restricting assumptions; and (3) the Detailed Design Phase (DDP) where a very fine FE mesh is used to analyze and solve stress concentration problems identified in PDP phase.

FEM analysis is also used by Joung et al. (2017a) in aluminum pressure vessels for deep sea systems, concerning the global buckling phenomena and the effectiveness of connection parts of the pressure vessel. Cherian et al. (2017) describe the design development of an offshore barge suitable for the transportation of heavy modules. In order to define the final dimensions of the barge, main focus was given on local and global strength considering various operations the barge was intended for. The structural design was based on the structural requirements and scantling calculations as well as on the ABS rules to define transverse and watertight bulkheads, web frames, longitudinal bulkheads, aft pump room construction, bollards, and sponsons. The structural design was then submitted to Finite Element (FE) analysis using ANSYS Mechanical. The philosophy behind the development of the FE model was to produce a relatively simple global model and then add detail to the critical zones where high tensions were expected due to the complexity of the geometry or due to the high stresses applied to the structure. The replacement of structural members such as stiffeners by equivalent plate thickness was also used as a simplification method. Local FEMs were produced and analyzed including the models of the aft pump room and the stern subjected to rocker arm loads. The purpose of these local models was to analyze or check specific structural characteristics that required more attention. For the specific case analyzed, the use of global and local FEMs with different levels of detail, proved to be a successful method to obtain the final construction on time with the required reliability and effectiveness.

Physical tests using scale models of ship structures are still very useful to evaluate the efficiency of the structural design of a ship. However, both experimental and numerical analysis require a detailed design and structural assessment of the physical model to be used in the towing tank. With this in mind, Dessi et al. (2017) documented their design approach and testing effort devoted to providing a reliable and well identified physical model before towing tests are carried out. Their main target phenomenon is the wet deck slamming, which is a challenging Fluid-Structure Interaction (FSI) problem for both experimental and numerical analysis. The study concludes that a systematic set of tests for identifying the structural properties of the elastic bodies interacting with the fluid, gives the chance to validate or even update the structural models included in the FSI solver.

Digital simulations of casualty scenarios are also being used to assess the reliability of the ship structures during the design phase. Ko et al. (2017) is one example of this approach, where specific ship-to-ship collision simulations in which a striking ship bow collides with the side of a struck ship, are studied. Their added value was to consider the structure of the striking ship also deformable, and therefore, capable of observing energy when the collision occurs. Nonlinear finite element method (NFEM) computations provided by LS-DYNA were applied for different collision scenarios, namely regarding the speeds and collision angles between ships. The results showed that the structural damages caused by a deformable striking ship bow are significantly different from the ones caused by a rigid structure. The maximum penetrations and structural crashworthiness between deformable and rigid bow models are different, which has impact on ship survivability or on the amount of oils spills. Rodrigues and Guedes Soares (2017) study the vertical loads progression caused by a flooding process for a shuttle tanker in full load condition, damaged amidships. Maximum values of the vertical bending moments are obtained and compared with the intact values. Parunov et al. (2017) use a NFEM to assess the residual ultimate strength of an Aframax-class double hull oil tanker damaged in collision and subjected to both horizontal and vertical bending moments. Two different types of damage are considered: damage of the outer shell only, and damage of both the outer and inner shell. Results for quick estimation of the damage ship's residual strength are printed as residual strength versus damage height diagrams. The procedure for rapid assessment of the residual strength is based on regression equations obtained from the FEM simulations, and according to the authors, may be useful for classification societies when developing rules regarding accidental limit states.

Vibrations affecting the ship structures have been taken into consideration by Dominguez et al. (2017) when designing the structural arrangement of ships. They consider the hydro-vibration analysis of the hull girder as a very important part in the design stages of the ship. Within the scope of their study, vibrations are mainly caused by encountering wave loads, or by the interaction between the ship's driveline and rudder. The methodology used to analyze the hull-girder vibrations induced by the propeller-rudder interaction of a coastal patrol vessel in the design phase is presented. The methodology considers the excitation of the propeller, the natural frequencies of the drive line, rudder, and structure of equipment foundations, the added mass and dumping of both the propeller and hull girder. Once more, FEM allowed to carry out structural modifications to comply with recommended limits of vibration effects. If applied during the design phase, the methodology may be used to detect possible failures, especially when there is resonance risk in the propulsion line.

Marinic-Kragic et al. (2016) proposed the Reduced Parameter Set (RPS) shape parameterization methods, which were compared to classical B-spline parameterization. It has been shown that the proposed shape parameterization methods are able to keep the shape generality while lowering the number of shape parameters on three mutually different test ship hull shapes. The developed multidisciplinary workflow integrating the proposed shape parameterization, hydrodynamic prediction tool and structural scantling rules proves that it is possible to have a numerical procedure that autonomously synthesizes the 3D shapes. The complex workflow was realized in modeFRONTIER using ANSYS Geometry Modeler, ANSYS Fluent and implementation of ISO 12 215 rules for composite monohull scantlings of small craft under 24 m.

Drimer et al. (2017) introduces a method for the structural design of planing hulls, which combines rules, theoretical solutions, and numerical analysis into a practical design procedure. The presented method provides an efficient tool for the determination of load effects when dynamics, hydro-elasticity, and nonlinear geometry are important, where existing design rules apply static linear assessment. The paper presents a database of simulation results in a wide range of parameters, practical for design. The direct calculations are valid for high strains, above yield, and the presented results may be used for limit state design as well. A limit state design needs to assess fatigue limit state as well, which is a scope for a future work. A design example demonstrates the application of the suggested method and shows a saving of about 20% of the bottom plates thicknesses, relative to design by rules.

2.2 Review of ship structural design for X

A summary of the most recent developments related to the design for specific performance aspects, also known as "Design-for-X" (DfX), is given in this subsection. 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 chapter. 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. Following the trends indicated by the work of the previous Committee, DfX is closely related to the current trend towards goal-based design methodologies in general and risk-based design in, endorsed by recent International Maritime Organization (IMO) regulations.

2.2.1 Design for life-cycle performance

Ventura and Soares (2015) presented development of voyage scenarios as a valuable tool in ship design for the estimate of the sailing and port times and operational costs. In the scope of the ongoing development of a software tool for the ship concept design, the voyage model was further detailed in order to support a more complete description of the ports and routes resulting in a more precise estimate of the port and sailing times, the fuel consumptions and the operational costs. The concept of voyage leg was expanded to allow the description of regions with specific environmental conditions or ship operation parameters. These enhancements are particularly relevant for liner ships, which have a higher number of port calls (by comparison with bulk carriers and tankers) and sail often with partial loads. The ship synthesis model was extended to include hull form generation, hydrostatics calculations, compartment modeling, EEDI and ship emissions estimates. A design procedure considering the ship synthesis model, the voyage model and the ship service conditions to be used in optimization procedures was presented. Some of the advantages of this implementation based on a spreadsheet is the possibility to use any design parameters as design variable and to have all the results exposed and available to specify constraints and to be used directly or indirectly (through utility functions) in objective functions, without the need to change the model. A simple numeric example was produced as a validation test of the functionality of the global procedure.

Lindstat et al. (2015) presented an interesting study that challenges the traditional environmental regulations approach for shipping activities. The study investigates the possibility of fulfilling the requirements for low levels of harmful emissions in ports and coastal areas without sacrificing the benefits at high seas of low cost bunker oil and its overall climate cooling effect. Continued use of HFO 2.7% Sulphur outside of the ECA in combination with clean fuels within the ECA is indicated to both retain the global cooling effect of shipping and reduce harmful emissions close to land. This indicates that IMO and other authorities should reconsider decisions to globally reduce allowable Sulphur content in fuels from 3.5% to 0.5% by 2020. Burning dirty fuels at high seas in an engine optimized for fuel economy (hence also raising the NOs), gives climate cooling benefits, and this more than compensates for the warming effect of reducing harmful SO_x and NO_x emissions close to land and human populations.

According to the authors, another problem with the IMO approach is that engines tuned to comply with ECA emission restrictions risk increasing greenhouse gas emissions, perhaps an irony of placing a ‘local first’ focus on environmental regulations. In addition, the study indicates that hybrid power setups give lower environmental impact than the standard engine solutions and a lower annual fuel bill. However, for fuel prices, which are 50% of the 2012–2014 average, the economic argument for investing in more advanced engine solutions weakens. One potential incentive to be considered forward is that vessels burning fuels with high Sulphur content beyond 2020 have to install either hybrid engine systems or advanced engine control systems linked to verifiable automatic reporting systems to ensure that the dirty fuel is burned only at high seas, and that the vessel complies with SO_x and NO_x obligations in the current and future ECAs. Implementation of such systems currently is entirely feasible technically.

Marques et al. (2017a) developed a simple and fast model to be applied in optimization problems about selection of marine dual-fuel low-speed diesel engines. Following that, Marques et al. (2017b) presented a new approach to perform the optimized selection of liquefied natural gas carriers’ propulsion system including the mainly financial aspects. It is an important study because with the new environmental restrictions the use of boil-off gas (BOG) is an alternative as cleanest than conventional fuels through dual-fuel diesel engines. A model to optimize the selection of LNG carriers' propulsion system towards synthesis, design and operation, as well as the needed models, has been presented. The work is based on a particular study of a ship that has to accomplish three different service speeds. The objective function maximizes the net present value of the project. Finally, this study can assist marine engineers and ship-owners to design and outline the operation of liquefied natural gas carriers.

Knight et al. (2015) presented a new type of real options analysis used to evaluate the worth of an option to Extend the Service Life (ESL options) of an aluminum structure from twenty to twenty-five years. It is an early application of Prospect theory-Based Real Options Analysis (PB-ROA) in naval design. PB-ROA abstracts the principles of real options analysis to suit naval design applications where the assets do not generate cash flows, and there for one cannot define value in monetary terms. Instead, the example in this paper defines the utility of a structural design based on three components: structural availability, cargo capacity, and producibility. The utility is contingent on risk factors like the time to crack initiation of a welding detail which is included using stochastic fatigue analysis. From an entire Pareto front of optimal structural designs, the options analysis exposes a partition in the design space which could be valuable in a design setting. The partitioning reveals the conditions in which certain candidate designs maximize the present value of future flexibility. Ultimately, this paper demonstrates a new approach to valuing flexibility in preliminary structural design that may generate useful insight for early stage decision makers.

2.2.2 Design for maintenance & repair

Raptodimos et al. (2016a) presented a framework for the acquisition of measurements pertinent to condition monitoring, maintenance and repairs of ships. Several types of raw signals are acquired. Acquisition at different frequencies was considered as well as the use of sensors, periodic measurements, or both. The suggested framework was evaluated in a case study performed on board a Panamax-class containership. Key data collection sources were identified through this case study and the data collection process was demonstrated. Raptodimos et al. (2015) also presented the data acquisition performed as part of EU FP7 Inspection Capabilities for Enhanced Ship Safety (INCASS) project. Both machinery and structural measurements were acquired. In the case of structural data acquisition, tiltmeters and Inertial Measurement Units (IMUs) were installed. This framework was validated on board a tanker vessel as part of an INCASS measurement campaign and further elaborated in a study by Raptodimos et al. (2016b).

Furthermore, data requirements of various maritime stakeholders including ship operators, Classification Societies, consultancy companies and maritime regulators and policy makers were described in INCASS project report (2014a). These requirements covered a diverse range of vessels (i.e. tanker, bulk carrier and container ship). This report additionally considered main machinery and equipment systems, sub-systems and components in order to derive a final selection of systems to be monitored and evaluated. Through this iterative process, the following components were identified: main engine, turbocharger, pump systems including fuel oil supply, lube oil as well as main and cargo pumps (tanker ship only). Dikis and Lazakis (2016) suggested a Machinery Risk/Reliability Analysis (MRA) tool that considers components' failure and degradation utilizing raw recorded data. The presented methodology involves the generation of a Markov Chain arrangement integrated with Bayesian Belief Networks (BBNs).

The latter framework is further detailed in (INCASS, 2014b). A case study was presented using simulated data of Main Engine (M/E) measurements culminating in a prognostic tool thus predicting physical (i.e. temperatures, pressure) and reliability values over time for the mentioned ship system. Complementing the above, Lazakis et al. (2016) suggested a Decision Support System (DSS) framework that utilizes the output of the MRA tool developing a user-friendly graphical interface (Dikis and Lazakis, 2016). Current performance is presented alongside warnings, failures, and in-depth analysis demonstrating the development of predicted information throughout the ship system and component lifecycle. Case studies of the DSS output using simulated faulty data as input is presented. Once raw data are acquired, the MRA and MRA DSS tools provide a complete solution for Condition Based Maintenance (CBM) of ship systems.

Additional work related to the design for maintenance and repairs of ship systems was performed by Taheri et al. (2016). The authors utilized a combination of BBN and Markov chains tor the reliability analysis and maintenance decision making for the lubricating oil system of a Suezmax vessel. Raptodimos and Lazakis (2016) presented a methodology utilizing Artificial Neural Networks (ANNs) in order to monitor and predict physical parameters of selected physical parameters in order to predict future values and subsequently propose correct maintenance actions and decisions. The suggested framework was validated through the prediction of exhaust gas temperature of a cylinder of a two-stroke marine diesel engine. Accordingly, Raptodimos and Lazakis (2017) combined the above with Fault Tree Analysis (FTA) in order to identify most critical ship systems and components.

Gkerekos et al. (2016) also suggested a database for the storage of machinery measurements and developed a self-learning model for the condition monitoring of ship machinery based on vibration measurements. This model was based on a two-class Support Vector Machine (SVM) classifier, able to discern between healthy and faulty observations. A case study based on data obtained through a measuring campaign showcase the soundness of the suggested database design. Furthermore, the vibration monitoring model was validated using a wind turbine dataset. In addition to the above, Gkerekos et al. (2017) also developed a self-learning model for condition monitoring of machinery components using raw physical data collected through measuring campaigns on board vessels. A one-class SVM classifier was developed. In this case model training was based only on observations that were deemed healthy. In the included case study, new data points were considered by the model and the model returned the similarity of new data points to the ones used for training purposes. Given a big-enough and diverse dataset, the suggested methodology can be utilized for machinery condition monitoring.

Li et al. (2016a) also developed an analysis tool that can provide long-term prediction of vertical wave bending moment which impact the ship structural loading and can thus provide information and early warnings for suggested inspection, maintenance and repairs of ships structural components. Accordingly, Li et al. (2016b) suggested a methodology where wave-induced vertical bending moment are estimated based on raw data obtained from onboard tiltmeter units. Both studies provided results which were shown in the developed ship structural DSS tool described in a study by (INCASS, 2014c).

Moreover, following the work performed by Dhillon (2006) who suggests an alternative perspective to design for maintenance and repair under the scope of maintainability, diligent inspection of systems in order to feed observations back to design stage and thus optimize design through this cycle. In this respect, Koch et al. (2016) provide an overview of methods that can be used for automated inspection of ship structures. First, robotic systems, including aerial platforms and magnetic crawlers are described in depth. The data that each platform can collect are discussed along with the relevant data analysis. Finally, data transfer options and data management are discussed. A thorough market survey of tools and strategies available for marine inspections is included in INCASS (2015a). There, the importance of robotic means for access and monitoring for inspection solutions is highlighted. Accordingly, Kolyvas et al. (2015) propose a photogrammetry-based methodology for remote visual inspection of vessels' cargo holds through 3-dimensional models. The suggested methodology aims to reduce the time required for in-situ surveying and lead to more targeted surveys. Photogrammetry applications on board cargo vessels are further discussed by Stentoumis et al. (2016). There, image data are combined with the data collected from a terrestrial scanner in order to increase the fidelity of 3-dimensional models. In this sense, data collection becomes semi-automatic and can be used as part of several hull-monitoring applications.

Ortiz et al. (2014) present a methodology for the inspection of internal and external vessel spaces through the use of Micro Aerial Vehicles (MAVs). Specifically, this paper focuses on the self-localization algorithm used. Positive results obtained from this application are also included. INCASS (2015b) discusses the processing and analysis of inspection data acquired through robotic means. Specifically, this includes the design of a mosaicking tool that stitches together multiple images captured by robots in order to supply the surveyor with image composites, allowing defects to be displayed in their full extension. Accordingly, environment reconstruction tools based on photogrammetry are included in order to build a 3D model of the inspected area. Additionally, novel defect detection tools that can work with both individual images and image composites are discussed. As the detection tools are based on image saliency, prior defect characterization is not required. Bonnin-Pascual and Ortiz (2014) describe the methodology followed for corrosion detection using automated visual inspection as a data source. In this case, two algorithms based on the combination of weak classifiers are proposed, Weak-classifier Colour-based Corrosion Detector (WCCD) and AdaBoost based Corrosion Detector (ABCD). These are trained to detect areas that present signs of corrosion. While misclassification tests showed comparable results from both algorithms, WCCD presented shorter execution times and better results when qualitatively evaluated.

2.2.3 Design for safety

Almost all existing conventions, rules and guidelines use descriptive language to satisfy the specific requirements of ship design. These requirements are called prescriptive requirements. According to the traditional ship design method, the safety performance of the ship is specified by the prescribed requirements. However, with the development of technology and the emergence of new design concepts, innovative designs that break through the existing prescribed requirements are emerging.

Currently, there are provisions in many IMO conventions for acceptance of alternatives and/or equivalents to prescriptive requirements in many areas of ship design and construction, providing convenience for the implementation of innovative designs. The International Maritime Organization (IMO) Maritime Safety Committee, at its ninety-second session (12 to 21 June 2013), approved the “Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments” (MSC.1/Circ.1455) (IMO, 2013). One approach to the approval of an alternative and/or equivalent design is to carry out a risk analysis for the alternative and/or equivalent design and compare it to overall risk evaluation criteria, which is called risk-based ship design method.

Risk-based ship design method is to integrate the risk analysis method and reliability analysis method into the design process of ships, which can provide guidance for the novel design. The risk assessment is carried out in the design stage of the ship. Then, the safety level of the alternative and/or equivalent design is compared with the traditional design based on the safety equivalence principle. Safety requirements are no long constraints, but optimization goals in this method.

Since 2014, the study of ship risk has been carried out mainly focusing on the comprehensive risk assessment of collision, grounding, fire, oil spill and other accidents. Research on risk-based ship design is relatively few. Konovessis et al. (2013) detailed a solution by developing a formalized methodology for risk assessment through effective storing and processing of historical data combined with data generated through first-principle approaches. The method should help to generate appropriate risk models in the selected platform (Bayesian networks) which can be employed for decision making at design stage.

Ehlers et al. (2014) suggested that ships transiting ice-covered waters are not designed according to physical measures but according to economic and empirical design measures. They introduced a holistic treatment of the design relevant features and their identification to improve safe Arctic operations and transport, mainly focusing on design relevant Arctic aspects related to extreme and accidental ice events. Noh et al. (2014) proposed a new methodology that combines dynamic process simulation (DPS) and Monte Carlo simulation (MCS) to determine the design pressure of fuel storage tanks on LNG-fueled ships. The combination of MCS with long-term DPS reveals the frequency of the exceedance pressure. The exceedance curve of the pressure provides risk-based information for determining the design pressure based on risk acceptance criteria.

Youssef et al. (2014) presents a Quantitative Risk Assessment (QRA) for double hull oil tankers that have collided with different types of ships. And exceedance curves are established that can be used to define the collision design loads in association with various designs. Zaman et al. (2015) conducted a complete Formal Safety Assessment (FSA) research in the Malacca Strait using AIS as a data resource. Yang et al. (2015) proposed a generic framework of risk-based winterization to facilitate the application of formal method and eliminate some limitations of the formal approach. Results from their article validated the effectiveness and feasibility of using risk-based winterization on vessel designs. Praetorius et al. (2017) presented the findings of a pilot study with the objective to introduce the Functional Resonance Analysis Method (FRAM) as a method to enrich FSA studies through structured expert input. The results of the study show that FRAM has the potential to enrich hazard identification as a complementary tool.

Risk-based design also has a wide range of applications in other areas, such as the civil engineering field. Maes et al. (2015) suggested that various civil engineering fields suffer from a perception that people fail to consider “beyond extreme” scenarios. They distinguished between three broad classes of events: far-out extremes for heavy-tailed hazards, scenarios marked by very unlikely combinations of events (perfect storms), and so-called unknowable unknowns and identified which objectives, which tools, and which risk measures can be used, and which lessons can be learned.

Reliability analysis is capturing the attention of ship designers regarding the structural arrangement, and Joung et al. (2017b) presents a study on the structural reliability and availability analysis, taking into account the uncertainties of material properties, environmental loads, and tolerance in construction, and the economic efficiency. A method to calculate the structure availability was developed based on the estimation of the failure probability for the structure design life. The target failure probability is then obtained by altering the CoV of the involved random variables, and the lifetime span and costs are computed based on the target probability of failure. The obtained CoV can be used as a guideline for the manufacturer.

In conclusion, the risk-based design concept has been gradually accepted in recent years. However, it is still in the development stage and its progress is relatively slow. the current progress and existing problems are as below. Risk-based design methods have attracted the attention of ship designers, and have been applied to the initial design (conceptual design) stage of risk-based design. The quantitative assessment methods and methods to deal with uncertain problems have had a certain development, such as the introduction of Bayesian network method, fuzzy set method and so on. Risk-based ship design methods are used in the design of new ships (e.g. polar ships), but the application is still few in a wider range of vessels’ designation. Consideration can be given to the design of vessels such as container ships and LNG ships. The current research is mostly focused on the analysis of individual ship or individual accident scenarios.

3. DESIGN TOOL DEVELOPMENT

Over the last few years, the development of the design tools for marine structures has been characterized by the extension of the software packages functionalities in order to create tools which can be used since the early design phases of a new ship, throughout its entire life. These design tools further integrate several aspects of the design of a ship, such as safety, hazard scenarios and risk assessment, life-cycle maintenance, accident scenarios, and optimization. The analysis of the state-of-the-art scientific literature has shown that integration of these functionalities in the design tools have led to two different approaches in the development of these tools: monolithic software, where the software house develops a single software package which integrates functionalities of other software packages, and modular systems, where the tool developers focus their activity on the improvement of the capabilities of a software package to interact and exchange data with other design tools. Furthermore, this section presents the recent progress on Computer-Aided Design (CAD) packages for ship design, focusing on the new 3D capabilities of this software and on the impact that 3D design is having on the maritime industry. Particular attention is paid to the development of Virtual Reality and its use in ship design. Later, the progress in new simulation packages for ship structural design is presented; in particular, the progress in the risk-based design software tools and in the structural optimization tools is discussed.

3.1 CAD Systems for Naval Architecture

Since the last ISSC Congress, the Computer-Aided Design (CAD) packages for the maritime industry have been reviewed and developed by many authors. The proceedings of ISSC 2012 (Pradillon et al., 2012) presents an overview of the main CAD systems which are widely used in ship design and ship building, and the capabilities of these packages to interface and exchange data with other specialized software packages that are used throughout the design-cycle of new ships. The updates of these packages were presented in the proceedings of ISSC 2015 (Collette et al., 2015), where the authors highlighted the efforts and the advances done by researchers and software developers in the triennium 2012-2015 in high-fidelity simulations and smooth data exchanges between CAD software packages and specialized design tools.

Since the last ISSC, this trend in the development of the CAD software packages has been continued and reinforced. We can divide CAD tools in two main categories: 2D drawing and 3D modeling programs. Several authors focused their research activities on the development of the 3D modeling of CAD software packages for the maritime industry. Larkins et al. (2015) highlighted that the use of a single 3D product model throughout the subsequent design phases of a ship can reduce design errors and production cost. The authors show the advantages that several companies have gained using 3D models not only for subsequent design phases, but also for interdepartmental communication and workflow organization using the Marine Information Model from ShipConstructor Software Inc. (SSI). The advantages of using 3D models are also highlighted by Morais et al. (2015) who use 3D modeling to support the management of welding processes on ships. According to the authors, 3D models provide intuitive visualizations and can be used to improve communication in a process that account for approximately 10% of total cost.

The advantages introduced by 3D modeling in ship design are partially reduced as 3D modeling is a time-consuming activity that requires to build-up a 3D model in the early design phase. In order to overcome this disadvantage, some authors have focused their research activity on the development of interface between different software packages in order to speed-up the creation of 3D models and allow the re-use of the same model in different analysis during the entire design of a ship.

Cabos et al. (2015) developed an interface between NAPA Steel and DNV GL’s POSEIDON for model re-use. In particular, the proposed interface allows the designer to interface a CAS system (NAPA Steel) with class rule calculation software (POSEIDON). The authors tested the new procedure and interfaces in the design of a 14400 TEU and the results of these tests showed a significant increasing in the efficiency of the hull design process decreasing dramatically the efforts for building a global POSEIDON structural model (The Naval Architect, 2015). Lindner et al. (2015) presented a modular system which combines a CAD system with a Product Data Management System (PDM) and allows the designers to create a 3D model used for the concept design of a new ship since the early design phases.

Koelman et al. (2015) developed a design system which interfaces a general purpose CAD system with specific ship design software packages. The system was tested in a pilot case where the internal layout of a ship, and in particular those structural components which are frequently modified during the design process (e.g. bulkheads and deck panels), was designed using the proposed design system. The results showed a reduction in the ship design time and a consistency of the system over the entire process. Moreover, the smooth exchange of data during the entire application implied that no performance degradation was experienced. Even if the authors recognize that this system should be developed more in order to be extensively applied to ship design, they emphasize that coupling dedicated software packages rather than developing monolithic software is a good strategy to improve data exchange among designers.

Building on the concept that big data exchange and efficient creation of 3D models are essential aspect to optimize design quality and reduce design time, several authors have recently developed interfaces and efficient data exchange systems in order to allow different dedicated software packages to collaborate with each other (The Naval Architect, 2016a). Morais et al. (2016) show that open architecture of software packages is the key to making a best-of-breed approach work. Indeed, open architecture of software packages allows the development of interfaces among specialized tools and allow the designers to use best-of-breed applications in each design task. In order to improve the 3D modeling potential of the software 3DEXPERIENCE, Dassault Systemes, class society Bureau Veritas (BV), the Shanghay Merchant Ship Design & Research Institute (SDARI) developed a pilot project where a single 3D model has been created for all the calculation and analysis performed using BV's VeriSTAR calculation tools (The Naval Architect, 2016b). Zagkas and Spanos (2015) present a unified designer-centered workflow between modeling and analysis which allows the designers to create a single 3D CAD model that can be used for structural and hydrodynamic analysis. This workflow simplifies the design phases and allow the designers to effectively use the CFD-based loads in the linear static FE analysis. The integration between CAD modeling and structural FE analysis has been also developed by Stilhammer et al. (2015) presents an integrated user environment for modeling and visualization called HyperWorks and developed by Altair Engineering. Acín and Kostson (2015) present a FEA system (Strand7) which can be used to analyze marine structures. The main innovation presented by this FEA system is the use of a programming interface (API) for the automation of repetitive tasks.

3.2 Virtual Reality and Augmented Reality

Concerning the trends observed during the latest decade, the future of ship industry will inevitably go through the use of Virtual Reality (VR) and Augmented Reality (AR) as key technologies for the design, production and operation of ships (Bertram 2017). Smarter design processes will consider the long-term economic and ecological pressure for energy efficiency. CAD (Computer Aided Design) systems towards 3D PDMs (Product Data Models) allow to perform a large variety of analyses and simulations, and the ship design is nowadays a simulation-based process. As result, simulation, Naval Architecture, and CAD/CAE packages are getting more sophisticated with more accurate geometry representation and more advance physical models.

According to Morais et al. (2017), currently there are two major players using VR in Maritime Industry: the Virtalis and the Techviz. Their main clients in this field are the DSNS (French Navy projects), the Keppel FELS (Offshore builder), the Hyundai Mipo Dockyard (one of the world's largest shipbuilders), BAE (British Navy projects), the Dalian (Big Chinese shipbuilder), and the Irving and Fleetway (Canadian Navy Project). Immersive VR systems such as big caves or head mounted displays, are only used by companies typically involved in defense or in very large-scale shipbuilding. Smaller companies building workboats, ferries, or yachts use CAD software's associated viewing applications. Although VR is accepted as a future key technology in ship design and shipbuilding, the fact that it has not been more widely adopted demonstrates that there are still serious concerns, particularly in shipbuilding industry. Morais et al. (2017) denote that the main challenges that are still being solved, are related to the lack of perceived benefit vs cost on using this technology, and the need for an up to date 3D model of the ship and ship structures. The solution for the first challenge consists in identifying in which areas does the VR brings real added value to shipbuilding, while for the second, is to make VR a natural extension of CAD and current workflows. This will lead to an increased adoption of VR in Maritime Industry.

A good example of the using these technologies is described by Cabos et al. (2017), where the use VR techniques for remote inspection of the hull and for structural condition assessment, is discussed. Currently, the survey of the hull structure requires the physical presence of a surveyor, however, with the use of upcoming inspection techniques such as drones and self-localizing cameras, opens window for the remote inspections, with lower costs, risks and time spent. In fact, a large portion of the surveyor's activity during the inspection, is related to physically accessing the structure for assessing hull condition. This, generally, is not an easy task due to narrow manholes in double bottom ballast tanks, or quite high elevations in cargo holds, and the accurate reporting of findings on the exact location, requires good orientation skills, for example, when examining a double bottom tank. Furthermore, the physical presence of the surveyor inside cargo or ballast tanks, requires a much more extensive, costly and time-consuming preparation of the structure and inner space, than an inspection performed by a drone or a robot.

Cabos et al. (2017) describe a scenario for remote hull survey performed by an autonomous or remote-controlled drone. The survey planning and preparation is done in office, which includes the identification in a 3D model of the ship, the target structures for the inspection. This will serve as a guide for the scanning task performed on-board by the drone. The spatial inspection data, which includes, geo-referenced photos and eventually measurements of thicknesses, deformations or cracks, is collected and mapped into the 3D model of the ship, which can then be explored by the class surveyor in virtual space using VR capabilities for navigating, orientating and interacting with the data on the virtual model reflecting the actual hull condition. The IRIS system described by Wilken et al. (2015) is mentioned as one of such system which captures (visual) inspection data inside hull compartments.

3.3 Specialized structural simulation packages

Over the last three years, we have noticed an increase interest in the development of specialized software packages for the design of ship structures using specific structural tools. The trend in ship transportation in building larger ships and the development of more advanced rules for class approval increased the request of specialized tools that allow ship designers to an accurate evaluation of loads acting on ship structures and on their response to these loads (Jörg et al. 2016). For these reasons, researchers paid particular attention in the development of new FEA software tools which include multi-physics analysis. Im et al. (2016) and Vladimir et al. (2016) developed a mathematical model, called WhiSp2, which can be used to perform an ultimate strength analysis of the ship structures taking into account slamming induced whipping. They applied the developed method to evaluate the design of a HHI SkyBench TM 19,000TEU ultra large container vessel. The hydro-structural analysis is performed using the code HOMER, while the ultimate bending capacity of the hull girder is evaluated using MARS, both these codes are developed by Bureau Veritas.

Multi-physics simulations for the evaluation of structural elastic response of ships and offshore structures have been also investigated by Ma et al. (2017). They proposed a new numerical coupling model between Smoothed Particle Hydrodynamics (SPH) and Structural Finite Element Method (FEM) in order to evaluate the Fluid Structure Interaction (FSI) behavior. This work complements the outcomes of a previous study developed by the authors on the coupling of SPH with a structure model with nonlinear beam developed to predict the occurrence of structural ringing under green water. The new numerical FSI numerical model allows fast simulations when both GPU acceleration and CPU parallel calculation technique are used. The results of the simulations presented by the authors and validated against experimental data in the case of a 2D beam elastic beam impact problem and this analysis shows the accuracy of the obtained results. Darie and Rörup (2017) developed a tool for the ultimate strength analysis of hull girders. The tool evaluates the load scenario using a hydrodynamic approach based on 3D Rankine method, the calculated loads are then transferred to a global structural FE model which is used to evaluate the ultimate strength ships by nonlinear analysis.

With regards to the Finite Element Analysis, we have noticed an increased interested in the development of automatic procedure for the generation of FE models and in particular in the improvement of the efficiency of the pre-process phase of the FE modeling, i.e. the development of the model geometry and mesh. The primary aim of these research activities is the development of procedure and software tools which speed up the pre-processing phase of FEA, decreasing the overall design cost. Korbetis et al. (2015) developed a method using ANSA preprocessor which allows designers to define multiple models which can serve different simulation analyses. The main advantage of this new tool is the automatic definition of different representations of the ship model according to the FE analysis that will be performed.

Korbetis et al. (2017) presented the new solver EPILYSIS for Finite Element Analysis (FEA), as the new product of the BETA CAE Systems software suite. In the paper, the authors describe two representative applications of the solver: the determination of maximum stresses and critical areas of a typical VLCC vessel subjected to three different loading conditions, and the analysis of a nonlinear-contact strength for a ship's rudder. Models' setup is conducted with the aid of the ANSA pre-processor, which generates detailed Finite Element models of the hull structures, complying with the meshing requirements of the Classification Societies. The results produced by the EPILYSIS are compared with a commercial FEA software using the META post-processor. Conclusions highlight the absolute coincidence between solvers regarding the deformation of the structure and the similar stress results for quadratic mesh elements. However, for triangular elements there is a much higher divergence. The authors also highlight the high performance of EPILYSIS, namely when the computation is parallelized.

Acín and Kostson (2015) presented some of the tools of FE analysis system (Strand 7) that can be used to automate repetitive tasks in FE structural analysis. The system presents a programming interface (API) that be used through most of the traditional programming language or development environment. Auto-modeling tools and procedures are also required by shipyards and ship designers of bulk carriers and tankers. The Harmonized Common Structural Rules (CSR-H) have been effective since July 1, 2015. The new rules have increased the required FE modeling of tankers and bulk carriers, since the FE model has to simulate the Fore and Aft parts of a ship, in addition to the midship part. Moreover, the mandatory areas for fine mesh analysis are also increased. This has affected the ship design, increasing the man-hours needed to perform the structural design and increasing the design cost of shipbuilders (Shibasaki, 2016). Myeong-jo et al. (2016) presented an auto-modeling tool which generates longitudinal FE models automatically using cross-section models for prescriptive rules analysis. They also introduced Auto-FE-Modeling which automatically generates FE models of ship structures, based on 3D CAD models. These tools are included in SeaTrust-HullScan, software tool developed by the Korean Register (KR).

The design of ship and offshore structures is characterized by a high level of uncertainty related to the shape of the structures, e.g. welding deformation, effect of misalignments, corrosion wastage). In order to evaluate the effect of the randomness of input parameters on the response of ship and offshore structures, designers and researchers usually use Monte Carlo Methods (MCM) combined with FE analysis. This method, called Stochastic Finite Element Method (SFEM), is often computational costly. In order to overcome this issue, Chen at al. (2016) developed an SFEM based on the Stochastic Response Surface Methods (SRSM) developed by Ghanem and Spanos (1991) that use Polynomial Chaos Expansions (PCE) instead of MCM. Chen et al. (2016) validated the new SFEM tool benchmarking the results of the methodology formulated for a 2D problem with the results obtained using MCM.

Some specialized software package may improve the structural design and the construction process. The developments in numerical methods have enabled simulations to reach the stage where it can solve an increasing number of problems that interest the shipbuilding and offshore industry. Caprace et. al (2017) proposed a benchmark study to understand the influence of the modeler's practice and FEM codes on the welding simulation outcomes. Results of various thermo- mechanical simulation models are confronted to the experimental results developed in ANSYS, SYSWELD, VIRFAC, and ABACUS. Although computational efficiency is a critical limitation of the application of computation welding mechanics (CWM) simulation to large structures, it is evident that welding simulation is quite successful in predicting welding distortion and residual stresses.

Several authors have recently developed procedures and tool to evaluate the structural response of ships and offshore structures subject to impacts. These analyses are usually performed using FE explicit non-linear general purpose software, such as LS-DYNA, ABAQUS, DYTRAN, NASTRAN, ANSYS. The high computational cost of these simulations trigged research activities aimed at the development of tools based on analytical methods that allow the estimation of forces and energy developed in ship collisions and allow the designers to select the worst crash scenario in a preliminary analysis. In this context, Principia and ICAM (Institut Catholique d'Arts et Métiers) developed the SHARP tool (Paboeuf et al., 2015). This tool is based on super-element method and allows the evaluation of crushing resistance of the impacted substructures, with respect to the penetration of the striking ship. The main advantage of SHARP is that it allows a fast evaluation of different collision scenarios. This allows the designer to identify the worst collision scenarios and to perform explicit FE nonlinear analysis on the selected case. More recently, Pire et al. (2017) developed an analytical simplified algorithm which allows the estimation of crushing forces and impact energy in an impact between ships and offshore structures. Yuan et al. (2017) also focused their activity on the development of a simplified method that take into account fluid inertia forces and fluid damping forces for the analysis of ship collisions.

3.4 Risk-based design software tools

In the European research field, ship safety research focused on the EU SAFEDOR project. Kaneko proposed for the ship risk assessment of the overall approach in 2002 and outlined the risk modeling methods in 2007. After years of development, the risk analysis method and reliability analysis methods has played a role in the design of ships, the alternative and/or equivalent design, and the development of regulations and specifications. The Safety Level Approach (SLA) is a risk-based approach, aimed at establishing a uniform risk level for ships and determining the risk level of existing rules. The safety objectives of ships are expressed in a risk-level way. In the case of risk-based ship design method, SLA can be used to develop safety objectives expressed in the form of risk.

Formal Safety Assessment (FSA) is an important tool for risk analysis and is of great importance for SLA and risk-based ship design. FSA method can evaluate the safety level of the existing rules and the cost-benefit ratio of the risk control measures required by the existing rules. One of the most important contributions of the FSA is to determine the risk acceptance criteria using the ALARP principle and conduct a comprehensive evaluation of the cost-benefit ratio to achieve the goal of adjusting the safety level. It is necessary to establish a complete risk assessment framework for ship accident to support risk-based ship design. Moreover, the risk-based ship design process has not yet formed a mature process framework.

3.4.1 Software Platform

Considering risk indicators as a standard of structural safety, it is necessary to carry out a risk assessment of the structure and to define a safety objective and a functional objective. According to the "Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments" (IMO, 2013), the main process of alternative and/or equivalent designs is as following:

- Preliminary design,
- Preliminary design analysis,
- Preliminary design approval,
- Final design,
- Final design analysis,
- Final design approval.

SLA can be used to develop safety objectives which are expressed in form of risk and FSA can play the role of a risk decision tool in the alternative and/or equivalent designs framework, the alternative and/or equivalent designs processes are shown in Figure 3.

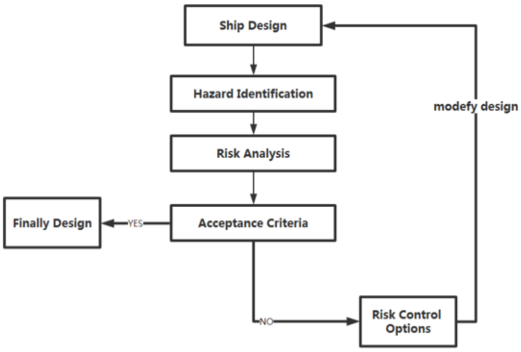

Figure 3: Risk - based ship design flow chart

The components of the software platform can be built based on formal safety assessment (FSA) software, including hazard identification tools and risk assessment tools. The function of the software platform can be mainly designed to provide assistance for the "Preliminary design analysis" process and "Final design analysis" process. The main function is to conduct safety assessments and verify whether the design ship will meet the risk acceptance criteria. In addition, the platform will put forward risk control options (i.e., improvements to preliminary design) to provide assistance in order to revise the preliminary design.

3.4.2 Hazard Identification Tools and Risk Assessment Tools

Regarding risk identification, lots of commercial software is available in the field of marine engineering, including PHA-Pro, Kyrass, Sabaton. These safety management software packages can be directly transferred from marine engineering to ship design and perform the same role in safety assessment. Hazard identification tools are designed to identify dangerous scenarios for the designed ships. For example, Sabaton is a software tool that supports Failure Mode and Effects Analysis (FMEA) and failure mode and hazard analysis. The results of the analysis are generally applied to design improvements to eliminate system failures or to mitigate component failure.

With regards to risk assessment, the software is divided into two categories: the first one is related to generic modeling tools, such as CARA-FaultTree for fault tree construction and analysis, and PDAT-Plus and Hugin for bayesian network construction and quantification. The second one is dedicated to a specific type of accident. This kind of software is more widely used in the field of marine engineering, such as ASAP, COLLIDE and son on. In the field of ship engineering, such software tools are much less, among which the CARCAT tool is the most perfect one.

The risk assessment tools are designed for the second step of a FSA process, determining the possibility and severity of the risk for the preliminary design, and comparing it with the risk acceptance criteria. The software CARCAT is a comprehensive tool with a full range of functions to assess risk and analyze the frequency and consequences of ship collision and grounding accidents.

3.5 Optimization Tools

The reports presented by the ISSC IV.2 – Design Methods committee at ISSC 2012 and ISSC 2015 Congresses presented a thorough analysis of the development of optimization methods and tools for the design, production, and life cycle management of ships. Both the reports emphasized the key role of these methods and tools in the design phases of a ship, as well as during ship operations where they are used as decision support tools to find out best alternative for ship repair tasks. Indeed, given the complexity of ships' structures and engineering systems installed on-board, the application of optimization methods to ship design and life cycle management can sensibly reduce costs without affecting vessels' safety and functionality.

Over the last three years, we have observed that these methods and tools have been developed further. This section presents the last developments of the optimization tools. Lee et al. (2015) presented a framework for optimal design of sub-structures of floating-type offshore wind turbine to be used in the early design phases. This framework is based on the neuro-response surface method (NRSM) and is composed of three parts: the definition of the geometry, the generation of the design space, and an optimization process. The authors tested the effectiveness of this method in the design of a 5MW TLP-type wind turbine. Yang et al. (2015) developed a robust design optimization (RDO) framework for the design of the supporting structures of offshore wind turbines. They applied the developed methodology to the case of a 5MW offshore wind turbine including in the analysis the metamodel technology with Kriging model in order to replace the time consuming finite element models for dynamic response analysis. The outcomes obtained applying this methodology where compared with the results of a Deterministic Optimization (DO) showing that the reliability of constraints in RDO was much higher than in DO and this implies that RDO is reliable even under the influence of uncertainties.

Pillai et al. (2016) also focused their research activity on the development of optimization tools for the optimization of offshore wind farms. In their study, they implemented a modular framework which uses a discrete genetic algorithm. The methodology takes a holistic approach to optimize turbine placement and intra-array cable network while minimizing the cost of energy. Kolios et al. (2016) extended the widely used Techniques for Order of Preference by Similarity to Ideal Solution (TOPSIS) method in order to take into account stochastic inputs. They implemented the proposed methodology in a numerical tool and they used the tool in the decision analysis of an offshore wind turbine support structures.

With regards to the development of optimization tools for the design of ship structures, over the last three years we have noticed that researchers have focused their activity on the implementation of tools which perform the optimization of structures in order to reduce the amount of FE analysis, tools for multidisciplinary optimization, and tools for ship shape and size optimization. Romanoff et al. (2016) presented a review of the development of a direct analysis approach which uses homogenization, finite element method and optimization. The homogenization is used to transform an originally periodic, stiffened plate or web-frame structure to an equivalent single layer (ESL) plate or beam structure, respectively. This speeded up the FE analysis and allowed the modeling of the stiffness and mass of complex structures accurately. Koroglu et al. (2016) implemented a procedure for the optimization of large ship structures using surrogate models. The procedure uses surrogate models which overcome the curse of dimensionality by a special decomposition method. The effectiveness of this procedure has been tested in three test structures and the outcomes showed the benefits of this procedure, including automatic design creation and optimization, effective usage of stream processors and model reuse.

The impact of the IACS H-CSR on the design of oil tankers and bulk carriers is discussed more in detail in Chapter 6. In this section, we want to highlight the fact that the entrance into force of these harmonized rules has drastically increased the amount of direct analysis of ship structures. Moreover, the structural design according to these new rules require the utilization of an integrated design system. Andric et al. (2016) developed a formal optimization procedure for the structural design of ships according to H-CSR rules. The procedure was implemented in a structural design system, called OCTOPUS-CSR which can be used in the concept and preliminary design phase. The authors tested the new tool in the design of new bulk carriers to be built in ULIANIK group shipyards, and they showed the efficiency of this tool in controlling structural scantling while reducing ship production cost. Kim et al. (2017) developed a multi-objective full optimization technique for the optimum design of hull structural scantling for merchant cargo ships that are modelled by plate-shell FE. The technique developed by the authors is applied to the structural scantling of a very large crude oil carrier (VLCC). They presented that using this procedure they are able to satisfy the strength requirements of the H-CSR.

With regards to multidisciplinary optimization, Stone and McNatt (2017) show how the integrated hydrodynamic and 3D finite element code MAESTRO can be used for the evaluation of the design loads, the structural response, working stresses, limit state evaluation, hull girder ultimate strength evaluation and structural optimization. In the paper, they optimized the cross section of a frigate minimizing the structural weight and maximizing the structural safety.

Optimization of hull size and shape has been investigated by Sugita and Suzuki (2016) who developed an algorithm for the optimization of hull sizing. In their study, the authors modeled this problem including a range of design criteria and an objective function which had to be minimized. The outcomes of their calculations were compared with the results obtained using the commercial software (DNV Sesam). Kragic et al. (2016) implemented a reduced parameter set parameterization method based on integral B-spline surface capable of both shape and topology variations. The authors applied this method in a multidisciplinary ship hull optimization workflow which integrated shape parameterization with hydrodynamic, structural and geometry analysis tools.

4. OFFSHORE STRUCTURES

4.1 Introduction

Exploration and exploitation of ocean-based resources such as oil, gas, renewable energies, seabed minerals or offshore food farming (fish or algae) has historically been the major driver for the development of offshore structures. A crude definition of an offshore structure is that of a structure or unit without permanent access to dry land, often required to stay in position performing its mission at an offshore location. Many diverse types of offshore structures exist and its classification is, to some extent, in the eye of the beholder. A reasonable first distinction may be made between fixed and floating offshore structures, from which one may intuitively derive that the latter structures are used floating either moored to the seabed or dynamically positioned, and the former structures are fixed to the seabed. Bottom founded offshore structures are steel jackets (with which the development of the offshore industry commenced), steel compliant towers or concrete gravity based structures (GBS). Spar platforms, tension leg platforms (TLP), semi-submersibles or ship-shaped (e.g. floating, production, storage and offloading (FPSO) units) units are examples of floating offshore structures.

Several aspects drive the option to employ one or another type of offshore structure. Water depth is certainly the main driver to depart from a fixed to a floating structure solution. Size and form are, in addition to water depth, determined by a variety of factors such as mission/function and associated requirements and environmental conditions. For instance, the same type of floating offshore unit will differ significantly when designed for oil and gas exploration (e.g. drillship or drilling semi-submersible) or for oil and gas production (e.g. FPSO, production semi-submersible); differences are even more pronounced for a certain type of offshore structure designed for different market segments, as for instance an oil and gas drilling jack-up vs. an offshore windmill installation jack-up. Function also allows distinguishing mobile offshore structures, units that are able to move from one location to the other to perform its task. These also come in different shapes and sizes and can work in a floating condition or supported at the seabed (e.g. jack-ups).

Despite sharing common ground in terms of design methodology, the particulars of each different design together with a strong dependency on previous specific experience lead to addressing design and associated methods separately for different types of offshore structures. Given the numerous types of offshore structures and its different purposes, book or textbook references addressing its design, and its structural design in particular, are equally spread as it is difficult and impractical to cover all in a single reference. This is shown in the paragraphs below where the Committee reviews books published on the subject of offshore structures design during the period covered by the current Committee's work.

The second edition of Bai and Jin (2016) aims to cover the latest developments in design codes, engineering practices and research in the field of marine structures. Several chapters are dedicated to offshore structures and despite the main focus being offshore ship-shaped structures, other types are also addressed. This new edition includes a noteworthy new chapter entirely dedicated to offshore fixed platforms and FPSOs, dealing with risk and reliability and asset integrity management considerations.

El-Reedy (2015) is a recent book publication allocating the focus wholly on fixed offshore structures and setting out to stand as a guide on structural design calculations pertaining to fixed offshore platforms, achieving this by systematically going through case studies and worked examples. Useful information on theory, principles, practices and design codes is also included supporting main goal of a more practical design guide. The book contains a whole chapter where a step by step guide covering the procedure for using software for the structural design and calculations of an offshore structure, which albeit being written for a specific software (SACS) may support the same procedure using other software tools. Another recently published book devoted to fixed offshore structures is Chandrasekaran and Jain (2017), which addresses the concepts of material selection, environmental loads, choice of structural form, construction and repair methodologies, structural health monitoring and rehabilitation of ocean structures.

Following the theoretical background provided in Part 1 of the Handbook of Bottom Founded Offshore Structures, the work of Vugts and Zandwijk (2016) presents various aspects of the fixed offshore steel structures during their full life cycle. All aspects from conceptual design, construction, installation, operation and structural integrity management to their eventual decommissioning and removal are covered in this handbook. Their study contains two chapters devoted to specific structure types – jack-ups and compliant bottom founded structures – where their particulars are treated from an introductory/overview level to detail structural design challenges. Overall this handbook stands as a solid, comprehensive reference for both students as well as practicing offshore engineers.

Chandrasekaran (2015) and Chandrasekaran (2016) are references targeting mainly offshore oil and gas structures. Both explain the fundamentals and advanced concepts concerning the design of the various types of offshore platforms and outline the different stages of marine structure analysis and design. The former focuses and elaborates on the integration of the concepts of structural dynamics with the FORM-evolved design of offshore structures. A structural engineering perspective drives the material of the latter reference, at the price of some neglect for other design aspects. However, the structural focus is the deliberate goal of the book, and in this sense, it serves is purpose as a useful complementary reference, for students or practitioners.

The encyclopedia of maritime and offshore engineering is a reference work covering the design, construction and operation of ships, offshore installations and other marine structures used for transportation, exploration and exploitation of ocean-based resources including oil, gas and renewable energy. It contains a volume devoted to offshore technology and structures, in which are included chapters dedicated to specific offshore structures, such as fixed, floating or jack-ups. For all topics covered this reference elaborates on all disciplines and aspects of the design of the structures, also including operational and regulatory considerations. Carlton et al. (2017) is a wide-ranging, up to date asset for anyone partaking in the life cycle of an offshore structure, a valuable addition to the library of any student or professional.

4.2 Design Methodology in Offshore Structures Design

Offshore structures design is, as in the case of ship design, an ad-hoc process, in the sense that all design considerations and the multiple engineering disciplines convene to a solution focused on the intended mission or function for the structure/unit. For this purpose, the design methodology used for offshore structures is intrinsically a holistic approach where the successful coordination of multiple technical and non-technical factors is the key to effectively arrive at the envisioned solution. All elements partaking in design are intimately interconnected, affect one another and ultimately the overall goal (mission performance). An illustrative example of this is given in Mendonça Santos and Alves (2016), where the authors describe the impact of stability considerations for a drillship on load carrying capacity and motions, then affecting structural design and its output, possibly influencing other aspects such as installed power and fuel consumption and following performance items like speed and station-keeping; all ultimately affecting cost and the overall design goal.

In essence, the design of an offshore structure/unit is hence always Design for X (DfX) multi-objective problem in which specific important performance indicators and properties are dealt with concurrently. In the context of offshore structures some of these design objectives stand out: design for operations and efficiency (mission), design for safety, design for environment, design for cost, design for maintenance and design for production. Irrefutably market and economic conditions dictate, at a certain point in time, the weight allocated to the different X's in the design process, though under no circumstances will any of these main factors be left unattended. For instance, as design for cost gains more weight due to economic reasons, design for operations and efficiency will remain as the primal goal, more attention will be paid to the design for production and maintenance but it is likely no compromises are allowed considering design for safety and environment. This fact has the positive effect of always pushing development and challenging the design of offshore structures.

4.3 Design Challenges, Progress & Trends

During the period covered by the 20th ISSC the offshore industry continued experiencing a downturn driven by low oil prices, market uncertainty and as a result severe cutbacks in capital expenditure by oil and gas companies. This has had a profound impact in the oil & gas and related segments (e.g. construction, support, etc.) and imposed new challenges and a rethinking of priorities as far as design is concerned. As mentioned by Anderson and Pickup (2017), this downturn has forced leaner cost structures, flatter organizations and is pushing for more efficient designs that will structurally lower the cost of development.

The shift of focus to cost adjusting to the new low oil price environment lead to significant changes to the paradigm of offshore structures/units design. None has been more impacted than the deepwater sector, as the challenges of water depth, remoteness from existing infrastructure and exposure to extreme environmental conditions render deepwater facilities "one-of-a-kind" designs, representing high complexity and high cost developments. Khurana et al. (2017) present the transcript of an industry panel discussion on the "lower for longer" oil price scenario highlighting design optimization and standardization as key innovations and design approaches for successfully achieving cost reduction for offshore project developments.

4.3.1 Standardization

A strategy of standardization and repetition is viewed as a promising opportunity for improving cost efficiency going forward, a point made by Hodapp et al. (2017) before discussing a design standardization for a floating production semi-submersible and pointing out some key elements believed necessary in achieving cost effectiveness through standardization: repetition of proven design vs. complex one-off design, scalability of the design for different demands, use of common design standards and specifications, use of standardized materials, equipment, fabrication and installation plans.

Standardization, including that of design, is a very noticeable trend and a subject of many publications by various authors, with a perceivable emphasis on the offshore floating production sector. Jung et al. (2017) describe the standardization of a FPSO hull going through design procedures dealing with establishing design basis, hull configuration, tank arrangement and structural scantlings for the midship section. A standardized and simplified production semi-submersible for marginal offshore field production is presented by Pallanich (2017), highlighting the effect of employing a proven hull design, an open truss deck forgiving with late equipment deliveries from fabrication and the importance of embracing a "going back to basics" in terms of design specification.

Tanaka and Takano (2017) address the challenges of applying a standard design for a FPSO solution and the authors propose a modular design and construction concept coping with those issues. Particular attention is given to modularizing structural design, methods and calculations employed to customize the FPSO hull and topside modules are described comprehensively. Other design considerations, such as hull form design, and used tools and methods are also covered therein. Example of success of implementation of standardization and related cost reduction on FPSO projects are addressed in Portella and de Souza Lima (2016), underlining design standardization as fundamental to improve construction productivity and cost reduction, and providing in depth considerations regarding the related structural design and analyses. Origins of these standard FPSOs can be found in de Andrade et al. (2015). Based on this experience, Nunes et al. (2016) discuss a study on its application on larger capacity FPSOs.

Tippee (2017) reports on a standardization JIP involving shipyard and classification societies aiming at improving design and construction efficiencies of offshore oil and gas installations. Details of this offshore standardization JIP are given in Lee et al. (2017), where insights into material, design, procedures and equipment standardization are presented and a methodology to pursue it is proposed. Wyllie, Newport and Mastrangelo (2017) give an owner and operator perspective on the benefits and limits of FPSO standardization, by reviewing different standardization approaches, looking back at previous examples and based on the design and operational experience suggest guidance on the achievable extent of standardization.

Classification societies have joined offshore industry efforts in reducing development costs, Benyessaad, Barras and Rocha (2017a, 2017b) propose solutions, such as the involvement of class from early stages of design and projects or embracing new technologies for maintenance, to the effect of cost reduction without compromising safety. The standardization trend is not exclusive to the deepwater sector, this focus on repeatability and optimization towards cost efficient designs is also being applied to fixed offshore structures. An example of the application of the "design once, build many" approach to the design of offshore platforms was presented by Gill and Henzell (2017), where the authors discuss the scalability, modularity and time and cost efficiency gains of such design approach.

4.3.2 Oil & Gas E&P Counter Cycle

Despite the fact that standardization has also been a recurring theme in the oil and gas exploration sector, here focus appears to be directed at specifications, requirements and procedures rather than standard designs. For instance, after a buildup of the drilling fleet with many units resembling one another, owners have recently pushed introducing unique designs and features for existing and future units so to differentiate themselves from the competition. Some design developments have been published following this set challenge of innovating and differentiating while keeping a tight leash on cost.

An example of this is the innovative drillship moonpool designed by Hendriks, Claassen and Chalkias (2015), targeting to reduce moonpool sloshing, increase safety onboard and reduced resistance and fuel consumption. Developed by extensive CFD analysis and later model testing, the new shape presents introduce new structural challenges overcome by also extensive finite element analysis and a design optimization in view of constructability. Hendriks et al. (2017) have proposed a transverse moonpool design which results in a reduction of hull cross section and structural integrity was verified by finite element analysis. Both the aforementioned references are also examples of a trend to incorporate CFD in early design stages with the purpose of shape optimization and as new unconventional shapes arise, so do the associated structural challenges. Other studies supporting this trend can be found in Darvishzadeh and Sari (2015) and Kim et al. (2015) both discussing the applications of CFD in offshore engineering. Scherl and Sodomaco (2016) is yet another example of a proposal for drillship with a double moonpool arrangement where the authors showcase the interaction between CFD and structural analysis in the design process. Relevant work on the derivation of hydrodynamic pressures acting on moonpool structures has been done by Rezende and Barcarolo (2017), who drew a methodology employing CFD analysis for that purpose. These results have a direct impact on the structural design and analysis of moonpool structures as this work has certainly been input to related Bureau Veritas rules and guidelines on the subject. Kim et al. (2016) presented a study on the strength and fatigue assessment of extended bilge keels for FPSO or FLNG units also using CFD in early stages of design.

It is recognized that the oil and gas exploration (drilling) and production markets are somewhat counter-cyclical, having its up and downturns out of phase. In the current low oil price status, exploration is on a downturn and operators are focusing on production and as a result attention has been more directed at production assets and consequently much research and design work has been dedicated to production units, such as the description of the design and fabrication process of the world's deepest production FPSO given by Moore et al. (2017).

A new shaped TLP to meet current cost reduction pressure was proposed and described by Zou (2016). The authors go about the several design tasks and compare the results for this new design with those of a conventional shape one and claim, amongst other things, it has more efficient structural design based on gains of reduced hull split forces and shear forces the structure is subject to. Kim and Jang (2016) document a global optimization method used for the preliminary design of a TLP using a simulated annealing algorithm that automatically controls the overall processes of modelling and assessment. More details on the application of this optimization algorithms to the design of TLP can be found in Kim and Jang (2016).

Antony et al. (2015) discuss the key drivers, constraints and criteria considered in the design of a spar platform. The authors document many aspects of the design process from early stages to final installation of the unit. Taylor et al. (2015) describe the design of a production semisubmersible based on a "one size fits most" philosophy which allegedly allows faster and less costly delivery schedules. Tian et al. (2017) discuss the hull sizing process of a proprietary semisubmersible production unit design by employing a methodology that allows generating a very large number of hull configurations then subject to a optimization routine to derive a final solution. The authors present quite some detail on the input used in the method including that of weight estimation.

The design philosophy behind a new light weight semisubmersible concept was presented by Wang et al. (2017), extensively documenting the hull structural design and analyses performed up to a FEED level on this 3 column production unit up. A tapered column deep draft production semisubmersible concept was proposed by Ye et al. (2017), featuring variable cross section columns in view of optimizing the wave force cancelation effects of conventional semisubmersible units. Covering many aspects of the novel design the authors present results from the global strength analysis confirming the feasibility of the concept. In line with the production assets focus Moe and Laranjinha (2017) take a different perspective and rather than considering a new solution the authors look into the converting distressed semi-submersible drilling units to floating production units. The authors outline a design methodology for this purpose, covering, amongst other things, technical requirement for the necessary structural modifications and upgrades.

Already on a growth path, liquefied natural gas (LNG) solutions have gained a boost in interest from the pressure of cost reduction throughout the industry as a cheaper alternative to common fuels with benefits of lower emissions. As a result several publications on LNG applications have been noted, such as, for example, the cylindrical FLNG unit proposed by Odeskaug (2015), the holistic approach to design and operate FLNGs by, Kheireddine et al. (2016) of DNV-GL, the article by Talib and Germinder (2016) covering the development of innovative FLNG solutions with considerations on the entire offshore-nearshore chain or the concept FLNG semi-submersible presented by Zou (2017). Vieira et al. (2016) present a comprehensive approach to the design of FLNG structures referred to as a synthesis approach which is based on considering many design aspects at an early stage, generating a large number of candidate solutions then used to make design choices towards an optimal solution.

4.3.3 Asset Integrity & Maintenance

The current low oil price environment has led to less exploration expenditure and oil and gas operators weigh their interest on production. A direct consequence of this is an increased focus on the existing installations, and the vast majority of the world's oil and gas facilities are mature assets, as mentioned by Haïdar (2016), who reports results from an industry survey showing that over 50% of the platforms are reaching or exceeding their design life. Asset integrity, life extension and maintenance have thus come to the center stage and much publications related to these subjects have been noticed. As noted by Rosen et al. (2016) the most cost-effective solution for producing assets in a low oil price environment is extending the life of the ageing structures past their original design life.

Boutrot et al. (2017a), (2017b) describes a methodology developed by Bureau Veritas for engineering reassessment of aging offshore units focusing on the two main degradation mechanisms: corrosion and fatigue. The use of a digital twin, its interface with conventional hydrodynamic and structural analysis and condition assessment calculations to build up a risk-based inspection program are some of the topics addressed. This work follows that of Boutrot and Legregeois (2016). Liu et al. (2016) presents the ABS class approach life extensions of floating production units, covering procedures and requirements for the related structural analyses of different types of units. Lloyds Register has developed a new cloud-based software with a target of 40% reduction in maintenance as well as operational expenditures for offshore assets, as reported by Leon (2017), another example of the growing employment of digitalization in this field. Moir (2016) presents an example of how an online monitoring system helped assessing the integrity of a North Sea platform. Lessons learned from a case study of an online asset integrity system is described by Wallace and Champlin (2016), highlighting the benefits of having accurate real-time data in place for managing the integrity of offshore assets.

A joint industry project was created on hull inspection techniques and strategy responding to the increased interest by owners of floating offshore assets designed to keep station for extended periods of time, e.g. FPSOs or drilling rigs. The goals and several pilot projects of this JIP are described by Constantinis (2017).

Gallagher and Rush (2016a), (2016b) describes a methodology and considerations for performing an early stage life extension assessment for offshore floating facilities and stressing that such assessment should be holistic, considering all aspects of the facility, not just an analytical assessment of hull strength/fatigue and moorings, Then followed by a general overview of design and construction decisions helping the planning and execution of a structural integrity management program while improving the long term structural integrity performance of offshore floating structures. Wisch and Spong (2016) present a recommended practice for structural integrity management of floating offshore structured, a draft of what may become a common use API document in the future.

Kemp (2016) describes the development and implementation of a risk based integrity management system applied to ageing production facilities and how this facilitated the process of life extension of the structures. Mat Soom et al. (2016) established a methodology for reliability-base design and assessment for ageing fixed offshore structures, applied to structural safety and integrity management, and having looking into the uncertainties of determining the probability of failure of the structures for its remaining service life. Agusta et al. (2017) formulated a decision theoretical basis for inspection planning of offshore structures based on Bayesian decision theory and Value of Information analysis. To illustrate the Value of Information based inspection planning approach the authors looked into an asset integrity management example concerning one fatigue hot spot for which optimal inspection and repair times were determined. Brief notes on further research and extension of the approach are also referenced therein.

Albright Jr (2017) notes the advances in drone technology and the increased interest by operators to include them as tools for inspection and maintenance of their offshore assets. The author discusses the particular problem of handling the process of data transfer, ingestion, storage and access, named “drone data dilemma”, in that scenario. On a similar topic Boman (2017) reports on ongoing progress in exploiting big data to create digital twins of oil and gas facilities and showcase on example pilot project of such technology driving costs down and increasing productivity on a drilling unit. Moir (2017) discusses the advantages of employing unmanned aerial vehicles (UAV) or drones for the inspection of offshore units. The ability to provide high definition imagery, video and thermal data for both general visual and close visual inspections with minimal interference with the unit’s operation and keeping humans out of the harm’s way make drones and effective, efficient and safe alternative to current inspection methods.

Applicable to asset integrity and maintenance of offshore structures is the study of Kefal and Oterkus (2017) that investigates the applicability of a new state-of-the-art methodology, called inverse Finite Element serving a structural health monitoring system providing real-time structural feedback on displacement and stress monitoring of offshore structures. Requirements on the design life of offshore structures are being pressed beyond the 20-25 years as existing installations are pushed to produce for longer than originally designed for. Acknowledging this fact Hernæs and Aas (2015) discuss an alternative approach to a longer design life, therein a 50 year span is considered, proposing a maintenance based design in which the structure and equipment would be continuously condition monitored allowing uninterrupted assessment of the remaining life of the assets. Canny (2016) presents an innovative approach to conduct well intervention and workover operations on platforms with limited structural capacity, the latter not being exclusive to aged facilities operating past their design life but rather a common challenge faced with smaller offshore platforms with wells drilled by jack-ups.

Current low oil price economics adversely affect the construction market as new build ventures are considered less favorable by operators. Still some relevant work related to construction is of noteworthy mentioned, such as the methodology development of modeling and simulation techniques for erection of modular construction of offshore platforms by Seo and Kim (2015). This methodology makes use of 3D laser scanning measurement data, a technology and technique also referred by Greeson and Waller (2016) as key to achieve accurate dimensional control in construction but also in a variety of offshore projects including setting of equipment, damage assessments, modification, refurbishment, and integration of structure, piping, and other components. Dai et al. (2015) proposed utilizing a heuristic genetic algorithm approach for offshore structures construction spatial scheduling taking into account uncertainties. Beckman (2016) reports on how the use of an integrated data system assisted and eased the construction process of offshore fixed platforms.

4.3.4 Design & Methodology Developments

The offshore industry is ever evolving and new structure types and shapes are being developed to either optimize existing solutions or to serve novel purposes (e.g. offshore renewables, food farming or seabed mining) and thus always pushing the development of offshore structural design. This report intentionally does not account for developments in offshore renewables which are covered by the work of Committee V.4. The offshore industry has seen a renovated interest in deep sea mining translating into publications of recent projects such as Chopra (2016) discussing the methodology and challenges faced during the design of the claimed first seabed mining vessel project. Starting with an overview of major milestones on deep sea mining projects of the 70's and 80's, Knodt et al. (2016) discuss the technology transfer between deepwater drilling and deep sea mining and present the state of the art engineering and technology developments applied therein. The authors also touch upon ongoing and upcoming deep sea mining research projects.

Aquaculture is another sector that has gained significant interest over the last years and a lot of research and development efforts are being made to move fish farming offshore. Following this new design solutions are being proposed, such as the ship-shaped and semi-submersible concepts presented by Lin et al. (2017) and Lin and Ong (2017) respectively. Both articles note structural design as a major challenge as a result of the departure from regular shapes and stress the need for further work and research to address it. Buck and Langan (2017) collect several publications on the subject of offshore aquaculture in which developments and projects are presented and considerations are made on structures for open sea aquaculture. Jack-up structures continue to stand as a significant and relevant work horse of the offshore oil & gas industry and its use in offshore wind turbine installation and maintenance has contributed to a continued interest and associated research and development on this type of structures.

Recurring topics are those associated with the design of spudcans and foundation analysis, as with installation and relocation operations. Zhang et al. (2015) propose a novel design aiming at improving foundation performance looking at global bearing capacity, spudcan fixity and resistance against punch-through. Lee et al. (2015) also look into novel spudcan shapes though the focus herein is on punch-through issues. Zhang et al. (2015) review the semi-analytical and numerical methods used in spudcan penetration analysis, by using large deformation finite element analyses and comparing it to experimental results the authors examine the existing guideline methods for penetration analysis. Fallah et al. (2015) used a probabilistic Eulerian finite element analysis to estimate spudcan penetration then compared with measured data and claiming the introduced method can produce reasonable prediction of spudcan penetration considering the uncertainties involved in the problem. A 3D large deformation analysis is also used by Zhang et al. (2015) concerning structural analysis required in jack-up reinstallation processes. Tho et al. (2015) present a case study of spudcan re-penetration analysis also using a large deformation finite element approach. Tho et al. (2015) compare coupled and decoupled approaches to interaction problems between jack-ups spudcans and the adjacent platform piles.

Tian et al. (2016) proposed an alternative numerical method to investigate the combined loading failure envelopes of jack-up foundations in soil. Skau et al. (2015) present a numerical study showing how non-linear hysteretic foundation behavior may significantly affect the overall dynamic behavior of jack-ups in extreme conditions when compared to that with a linearized foundation model currently standing as industry practice. The authors make aware that generalization of the presented analysis procedure to all jack-ups and conditions may not be applicable, suggesting the need to extend the study to broader set of units and conditions.

A procedure for establishing non-linear stress-strain relationships to be used as input to finite element analyses of jack-up footings was presented by Jostad et al. (2015), calculating non-linear load-displacement relationships (foundation stiffness', which play an important role on dynamic behavior and structural utilization of jack-up platforms) of the individual footings are then divided into cyclic and total (average plus cyclic) components to be used as input to the dynamic and quasi-static structural analyses of the jack-up. The authors compare the obtained bearing capacity envelope and rotational stiffness' with industry standard practices concluding the latter fail to guarantee conservative results in some cases.

For drilling jack-ups which tend to stay on location for longer periods and hence are subject to less relocation operations, boulders are generally removed from the location where the rig is to be installed. In the case of windfarm development, the frequency of jack-up relocation is such that renders such operation uneconomical. Following on this Curtis and Allan (2015) conducted a finite element study on the interaction between boulders and jack-up spudcans with the intent to provide some guidance on deciding on boulder removal for jack-up installation. Another possible issue encountered during jack-up installation is the interaction with existing subsea templates, which is dealt with by Engin et al. (2015) by using two finite element modeling approaches for spudcan penetration analysis and trying to overcome difficulties encountered by using conventional large deformation finite element in such studies.

Carre et al. (2017) showcase how using an advanced simulation model has helped in optimizing jack-up relocation operations, encompassing extraction and installation analyses. The described methodology accounts for soil stiffness, spudcan shape, jacking speed, and compares the calculated loads with the structural capacity of the legs and jacking system to obtain permissible wave height curves. A simplified spudcan-soil interaction analysis for touchdown during jack-up installation was investigated by Chang and Liu (2016), using CFD and finite element simulations for the purpose of establishing touch-down operational limits.

Koole and van der Kraan (2015) review dynamic behavior phenomena pertaining to the design of modern jack-ups, looking into the methodology described in the readily available guidelines and covering important topics of wind loading and the push of using jack-ups in deeper waters. Janssen et al. (2016) show the effectiveness of the proposed add-on spudcans in extending the operating capabilities of jack-ups in view of operations in deeper waters and associated higher environmental loads.

Ha et al. (2016) discuss recent damages to living quarters (LQ) structures of jack-ups reported during tow due to slamming and green water phenomena and subsequently propose an engineering procedure for the structural design of jack-up LQ structures considering global and local loads in the finite element model in a departure from commonly used simplified models.

Ji et al. (2015) describe the different finite element analyses and models required for the structural assessment in the design of jack-ups. McLaren (2017) looks into effective leg buckling length factors used in the calculation of leg axial strength of single member leg jack-ups, focusing on the leg-hull interface the author considers how accounting for the stiffness of the global system and the load distribution between legs can lead to more appropriate values for buckling length factors. Mobbs and Stiff (2017) discuss the development of an approach to assess effective shear areas of jack-up chords. On the subject of jack-up under vessel impact, Raithatha and Stonor (2015) investigated the ability of the jack-up to survive the vessel impact by means of an effective non-linear dynamic analysis. Levanger et al. (2016) describe the use of non-linear finite element analysis accounting for progressive change in the contact surface and stiffness of impacted jack-up leg and impacting vessel in the assessment of the collision response of a jack-up.

Rules and regulations often become a design driver by triggering the reconsideration of previous design assumptions due to newly introduced requirements or the questioning of the validity of long standing requirements in view of market developments. Ebrahimi et al. (2015) discuss how rule changes influence the design and performance of offshore vessels and criticize the lack of balancing perspective methodology leading to possibly unnecessary cost overruns in future designs and call for a reality check advocating for a criticality review of new regulations by the industry. On a similar note Carra et al. (2017) outline the methodology for establishing robustness criteria for FPSO design in view of handling low probability extreme events. Kitchen (2015) deliberates on how rules and regulations can impede design innovation of spar structures and discusses how risk-based design could replace traditional prescriptive rules and stand as a better solution to allow design innovation meeting actual market drivers without compromising safety. After recent incidents of wave impacts on semisubmersibles structures, the regulatory regime pertaining to air gap considerations and related structural requirements has been review and updated. Pessoa and Moe (2017) look into this subject and investigate the impact of the new rules on the design of drilling semisubmersibles, namely by comparing it to current industry practices.

Yu et al. (2016) have proposed a novel load and resistance factor design (LRFD) based design criteria for the design of mobile offshore units and floating production units, claiming a better compatibility with the working stress design (WSD) criteria which is quite popular in the offshore design community. As a verification exercise the authors present study cases of a column stabilized production unit and a jack-up unit.

Design methodologies and new tools used in the design of offshore structures continue to progress driven by the everlasting pursuit of development and effort to ease the execution of complex tasks. Such an example is the dynamic sub-structuring approach to improve the current practice global structural dynamic analysis of topside/hull systems proposed by Majed et al. (2016) claiming the higher fidelity of the presented method will render local models and analyses obsolete thus with direct time and cost savings in the structural design process. Oh et al. (2017) propose a novel finite element approach related to the analysis of load-carrying structures with nonlinear contact and frictional behavior, e.g. LNG independent tanks and hull structures, based on static load and stiffness condensation. Kim et al. (2017) introduced a method to design the arrangement of offshore platform topsides by means of an expert system and multi-stage optimization. Presenting a benchmark study based on a FPSO the authors suggest such method can yield optimal arrangements.

Maslin (2017) reports on the application of artificial neural networks to aid in the design of floating production units during the concept and early stages of design. By input of previous FPSO design data, the neural network system will learn from it and being linked and able to perform several engineering calculations makes the design iterations and the evaluation of different solutions a much easier task. Engebretsen, Shu and Borgen (2017) have used artificial neural networks to estimate hydrodynamic sectional loads for FPSOs.

4.4 Survey on Offshore Structures Design Software

The Committee conducted a survey on software usage in offshore structures design and its results are presented and reviewed herein. A web-based survey was distributed amongst stakeholders in the offshore industry with the objective of identifying the tools and software being used in and for the design of offshore structures and related activities (e.g. engineering, construction, etc.). Other goals of this survey comprised trying to note different tools used by offshore vs. ship designers as well as trying to identify existing differences related to the main activity of the stakeholders and tool usage nuances associated with different offshore units/structure types. The survey also examined the subjects of software and tool integration in the design of offshore structures and the use of new technology in the design process.

4.4.1 Overview and characterization of respondents

Despite the survey being sent to a large number of industry players, being easily accessible and having a limited number of questions, the Committee only received fully completed survey answers from 23 respondents. It is acknowledged that the sample size may be small and hence insufficient for statistical inference at a desirable confidence level. The gathered answers are however deemed to be representative enough to show trends and draw indicative conclusions.

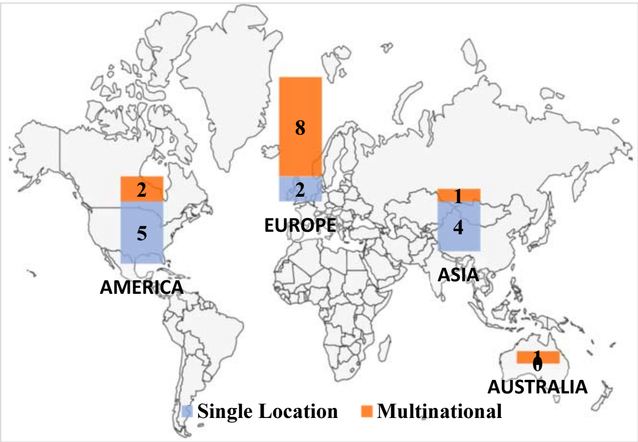

Figure 4: Survey respondents – regional distribution & international presence

Figure 4 provides the total number of respondents and their regional distribution, where the respondents were grouped per continent (America encompassing North and South Americas). The offshore industry is worldwide spread, however the numbers give an indication of where the major hubs/clusters are located, America and Europe being where the industry is more mature. It should be noted that Africa is very important and established offshore market, though the expression of local companies involved in the design, engineering and construction of offshore structures is small.

A distinction with respect to international presence was made by splitting the companies into multinationals and single location. The reason for this lies in the fact that the vast majority of players in the offshore industry (alike commercial shipbuilding a true global market) act on a worldwide scale irrespective of having presence in multiples locations (herein called multinational) or at a single location, i.e. single location does not translate into local business. The latter is the case for 100% of the companies that participated in the survey. There is no correlation between this differentiation regarding international presence and company size, i.e. several companies have presence in multiple regions but still are small or medium enterprises (less than

500 employees) and typically shipyards are enterprises with a large number of employees at a single location.

Company profiles are portrayed in Figure 5 showing the companies' distribution by primary activity and per region. Results corroborate the known fact that Asia is the epicenter of construction, all respondent shipyards being from this region. Only one of these shipyards works exclusively for the offshore industry, the other four working in the merchant shipbuilding industry as well. One company indicated its primary activity as design, construction and operation of FPSO units, thus being an owner.

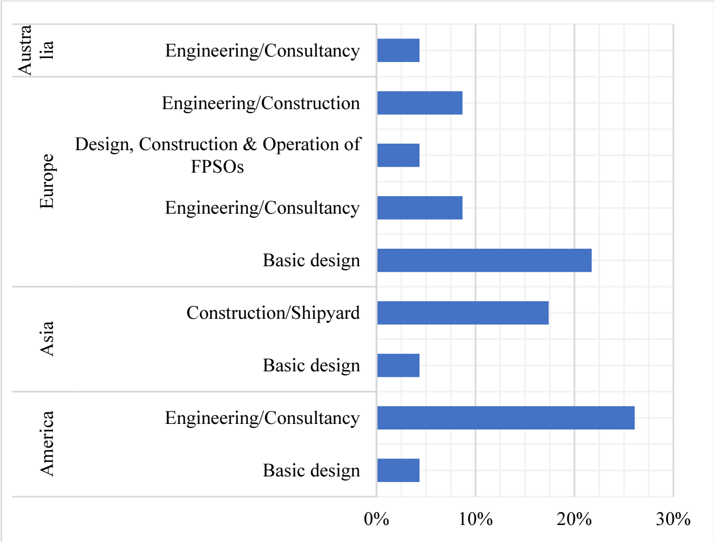

Figure 5: Company primary activity

It can be noted that there is a significant number of companies having basic design as primary activity suggesting a larger number of independent design houses when compared to the shipbuilding industry. This is further evidenced by the fact that out of the 43.5% companies that indicated being involved in a single activity, half are dedicated to basic design of offshore structures/units. The remainder of the companies have indicated be involved in multiple activities related to offshore structures/units, the distribution per activity is shown in Figure 6.

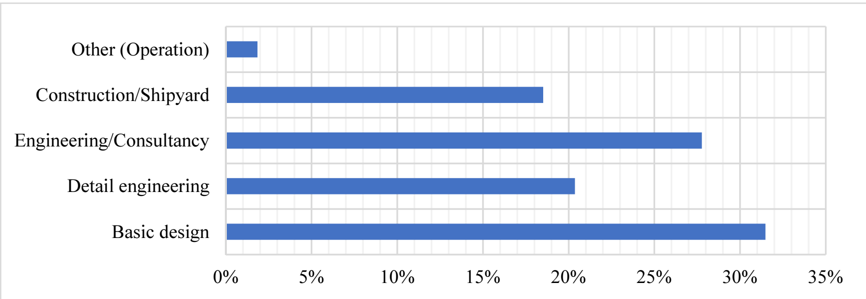

Figure 6: All activities related to offshore strucutures/units design

The vast majority of companies (91.3%) are involved in the design of different types of offshore structures/units, only a few are dedicated to a single type. Circa 71% of all the companies work in the mobile offshore structures/units market, 61% being involved with floating offshore structures/units. The share of companies participating in the survey that are involved with fixed offshore structures is smaller. The distribution of type of structures/units in the companies' work portfolio is pictured below, at a glimpse these results do not really mirror the population of existing offshore structures/units when considering fixed vs. mobile structures or even considering the different types of mobile structures/units. Yet these results give an indication of size of the market in terms of parties involved in the design of the different type of structures.

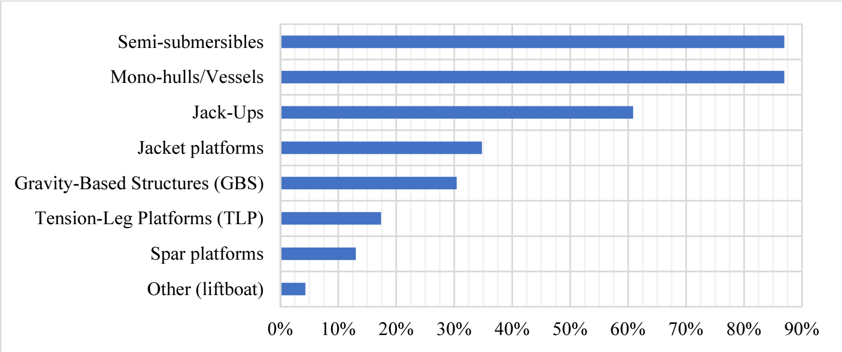

Figure 7: Type of offshore structures/units

No correlation was found between structure/unit type and region, confirming the earlier statement with regards to the global nature of the offshore industry but also that the different types of structures/units are employed offshore worldwide. With respect to the mission/function of the offshore structures/units most companies indicated to be involved in a multiple sector, only two companies indicating to be dedicated to a single purpose structure/unit. The results (Figure 8) show, as expected, that the largest share is taken by offshore units for the oil & gas market.

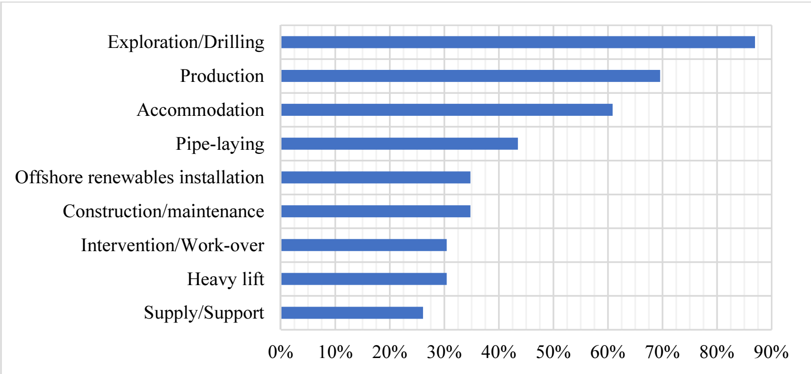

Figure 8: Mission/function of offshore units

4.4.2 Naval Architecture Tools

A large number of different software suites was indicated to be used regarding the design of hull and/or shape of offshore structures (Figure 9). Most companies employ multiple tools, only 2 companies having indicated the use of a single software tool for this purpose. Noteworthy is the usage of 2D tools (91.3% of all respondents) for this purpose, and still 13% have noted to use 2D tools only. Another interesting point is the high percentage (43.5%) of use of engineering calculation software for designing hull/shape though this result is likely to be biased by the large number of respondents involved in engineering and consultancy work that are likely less involved in early stages of design when hull/shape is developed.

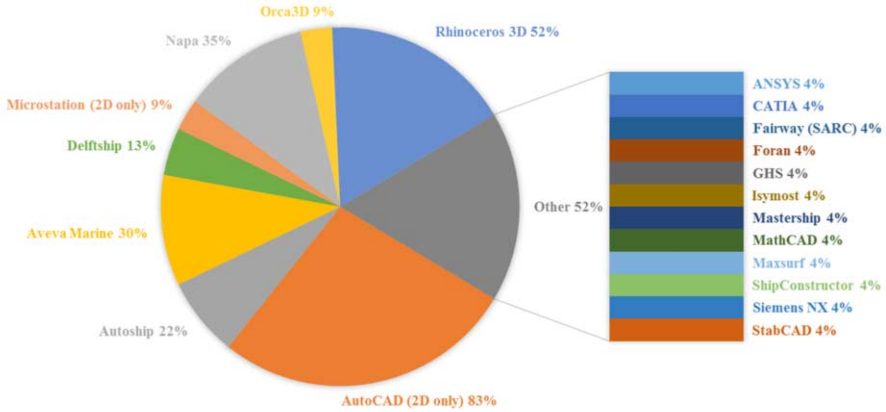

Figure 9: Hull/shape design software usage

AutoCAD is the predominant tool used in 2D drafting tasks, as can be seen from the replies outlined in

Table 1. In fact, only 3 out of the 23 respondents have indicated to use another tool in addition to AutoCAD. Irrespective of the size of or primary activity of the company, all use it, making AutoCAD the standard in 2D drafting.

Table 1: 2D drafting software usage

Software	**Usage**
AutoCAD	100%
Microstation	13%
Draftsight	9%

Shipyards & engineering/consulting companies are the users of integrated naval architecture suites, both shipyards and larger engineering/consulting firms using multiple packages. Overall 71% of respondents have indicated that they used a naval architecture package as a tool in the design of offshore structures/units. The usage of such integrated packages amounts to 29% for companies primarily involved in basic design which is considerable. It is noted that the larger, more complete (in terms of integrating more design aspects and tools) suites, such as Aveva Marine or Napa, take the larger share of usage (Figure 9).

Regarding the tasks performed with integrated naval architecture packages, results suggest these suites are utilized equally at different design stages (Figure 10) and those using these tools do so covering all design activities they are involved with. Usage for fabrication and assembly management scored lower as this matches the number of respondents involved in actual construction activities. It is interesting to note that one company has opted to develop an in-house integrated naval architecture tool; in-house development of tools of such magnitude is somewhat unexpected.

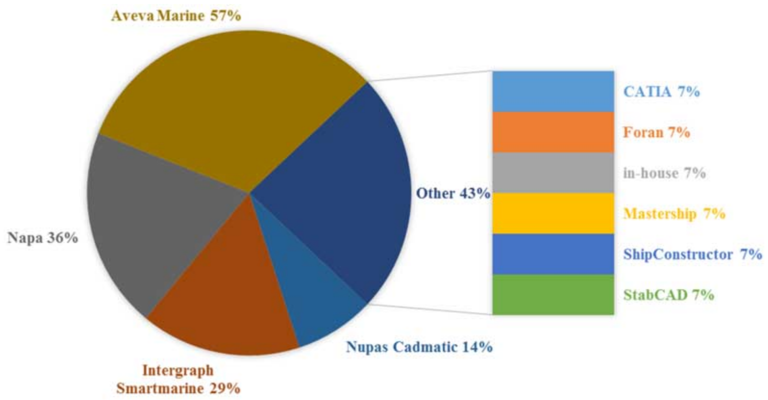

Figure 10:Use of integrated naval architecture packages

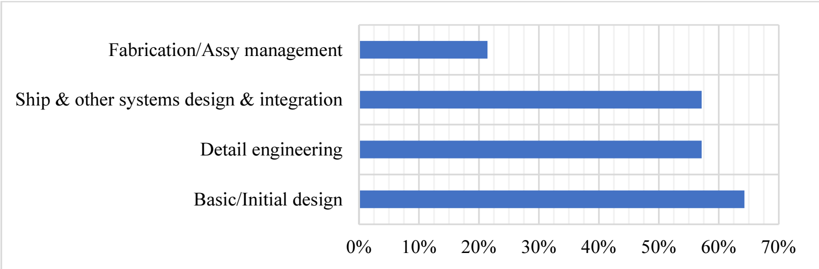

Figure 11: Tasks performed with naval architecture packages

Only 2 out 23 noted not to perform stability calculations in the offshore structures/units design loop. Most companies opt for a single tool for such calculations (circa 71% of those performing stability analysis). The distribution of the different tools used is pictured in Figure 12.

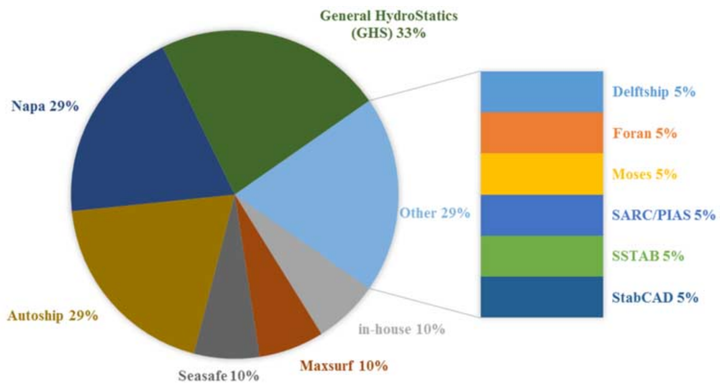

Figure 12: Software used for stability analysis

The number of respondents performing hydrodynamic calculations is similar to that reported for the case of stability analysis; only 3 out of 23 do not include hydrodynamic calculations in their offshore structures/units design efforts. With respect to usage of multiple tools, the scenario is the opposite as in this case only 20% of those performing such tasks employ a single hydrodynamic calculation tool.

The results for usage of software hydrodynamic analysis have been grouped in high level bins: commercial, classification society and other (accounting for in-house developments) tools. The main reason for this is to identify the usage of software developed by classification societies despite the fact that these are also commercial in the sense of being available in the market and competing with the other existing packages (note in addition that in the field of hydrodynamics the weight of rule and regulatory items is less significant when compared to other disciplines, e.g. structural design). It is interesting to note the very significant portion of usage (55% of those using hydrodynamic software) taken by software packages developed by the classification societies. The results show (Figure 13) that Wamit and Ansys Aqwa are the hydrodynamic calculation tools preferred in the offshore industry. Noteworthy to mention that only one integrated naval architecture package was indicated as a hydrodynamics analysis tool.

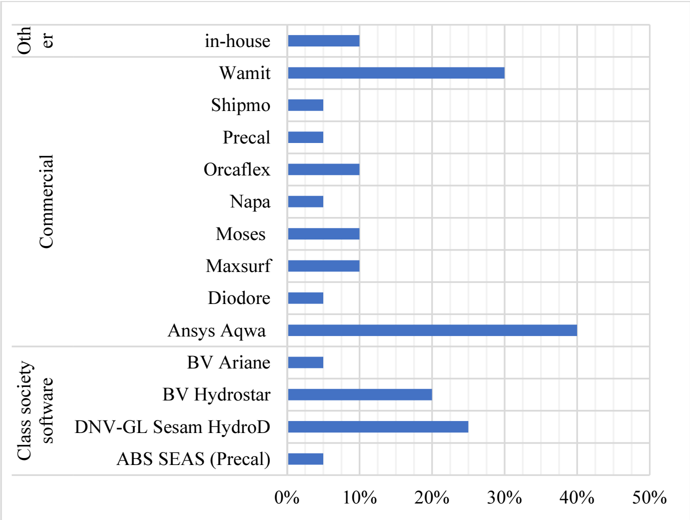

Figure 13: Software used for hydrodynamic analysis

In reply to the question of whether computational fluid dynamics (CFD) was being used in the design process of offshore structures/units, 35% of respondents indicated to perform CFD analysis as part of the design process, and considering those employing CFD analysis in the design, all have as primary activity basic design, with one noteworthy exception of a shipyard. The distribution of tools employed in CFD analysis (percentages amongst those performing it) is presented in Table 2.

Table 2: CFD analysis integration in the design process

Software	**Usage**
CD-adapco Star-CCM+	62.5%
OpenFOAM	25.0%
ANA (LEMMA)	12.5%

4.4.3 Structural Design Tools

Most parties use multiple tools in the initial design stage, in particular regarding scantling design, only 36% of respondents indicated to solely use classification society software. Results suggest a common practice of a balanced mix of hand calculations, in-house tools (e.g. spreadsheets) and classification society software specific for that purpose for establishing main scantlings in early stages of structural design (refer to pie chart in Figure 14).

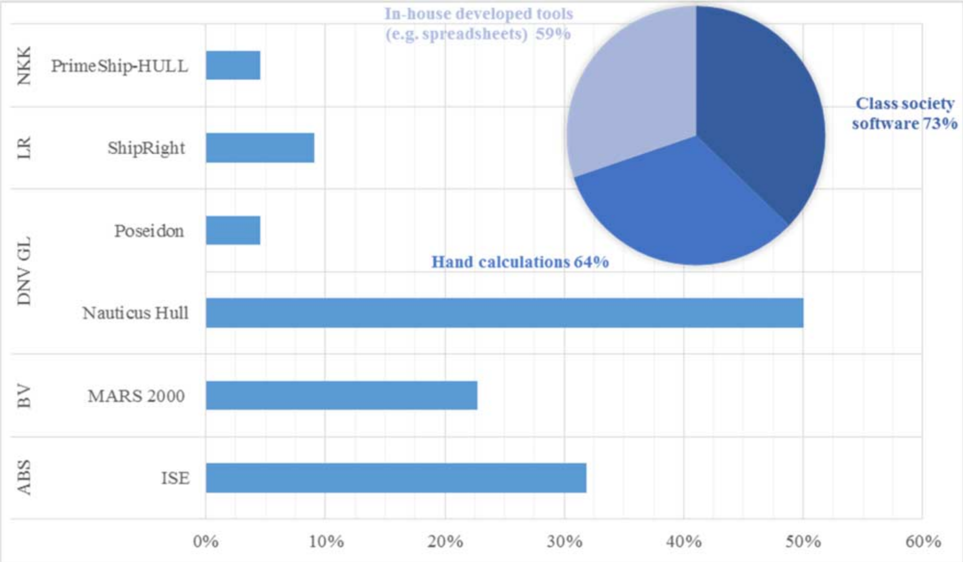

Figure 14: Tools used in structural early design stage

Drilling down into the Classification Society software used for scantling design one can notice the largest share is taken by DNV-GL, ABS and BV. These results confirm expectations noting that these Classification Societies (especially DNV-GL and ABS) lead the market in terms of offshore structures/units in class. All companies incorporate finite element analysis (FEA) in the structural design process and the primary tool of choice for this purpose is a commercial software (75%) vs. classification software (15%). The differentiation between commercial and Classification Society software is more significant in the context of structural design since the Classification Society tools tend to be specifically developed for the marine and/or offshore industry albeit having the possibility of being used as generic FEA packages as are their commercial counterparts.

There is an almost equal split between companies using a single FEA tool and those using multiple, there is, however, no correlation between company primary activity and the use of multiple FEA tools. It looks as though that the use of multiple FEA tools is correlated to companies being involved in the design of multiple offshore structures/unit types. The distribution of use of different FEA suites is shown in Figure 15. The Classification Society software has not been scrutinized as the large number of different tools was deemed too detailed for the purpose. A review of classification software may be found in this Committee's ISSC 2015 report, many tools overlapping ship and offshore structures design.

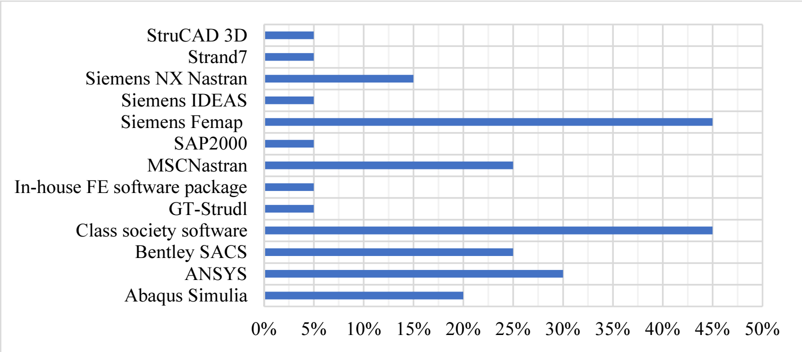

Figure 15: Software used for finite element analysis

The task of checking rule and regulatory compliance for FEA is primarily handled by the use of in-house post-processing tools integrated and interfacing with FEA packages, this being the case for 90% of the respondents (Table 3), circa 48% using only such tools for the task. Second in line are classification society software suites, with a share of 55%, and a quarter (25%) of the respondents indicated to perform rule and regulation compliance checks exclusively with such software. No correlation was found between company primary activity and tool choice.

Table 3: Rule & regulation compliance check for FEA

Tool	Usage
Class society software	55%
In-house FE software package	5%
In-house post-processing tools integrated/interface with FE packages	90%
SACS	5%

As for rule compliance checks, in-house developed tools are the preferred choice (Table 4) for managing the hydrodynamic load transfer to FE in direct calculations and 52% of companies performing direct calculations (73% of total respondents) resort only to these tools for this purpose. Again, the second tools of choice are classification society software. Also in this case no correlation was found between company primary activity and tool choice.

Table 4: Tools for hydrodynamic – FEA interface

Tool	Usage
ANSYS AQWA	10%
Class society software	30%
In-house package	10%
In-house post-processing tools interface with hydro-FE packages	80%

The greater part of respondents includes structural optimization as part of the design process (refer to Table 5). The tasks and/or goals of structural optimization vary, though a trend for weight optimization is patent in the responses. With respect to tools employed, the choice seems to lay with commercial software tools, in particular with generic FEA packages having structural optimization capabilities.

Table 5: Structural optimization in the design process

Is structural optimization part of the design process?	Yes: 71%	No: 29%
In which cases is it used?	**Tools used:**	
• To facilitate construction and decrease the weight; • Principal dimensions of hull, structural arrangement, shape of main supporting members, etc.; • Initial scantling evaluation together with FE verification; • Determination of scantlings in relation to span-spacing for weight optimization; • Location and amount of bulkheads in relation to structural efficiency; • Elevated Conditions (jack-ups); • Follow minimum basic scantling rules, and then reinforce critical areas only as needed minimizing weight	• Nastran • Ansys • StruCAD • Abaqus • In-house tools	

4.4.4 *Software Integration & New Technology*

The design process of offshore structures/units involves direct calculations to a great extent, the departure design solely on the basis of prescriptive rules being the norm. This fact makes the issue of software integration and interface between different design tools very significant. In order to understand and paint a picture of the trend of development regarding this matter, the survey included a set of questions where the respondents could scale their degree of agreement. These questions are transcribed in Table 6 and the answers are shown below (Figure 16).

Results suggest a trend towards agreeing with the need to put effort into having the existing tools and software develop into fully integrated packages with smooth interface between different disciplines and/or design tasks. This is further reinforced the portrayed disagreement with respect to development being focused on the separate packages and the agreement with the need to have commercial tools strengthen the capabilities regarding integration of different packages/tasks rather than this being done via in-house developments.

Table 6: Offshore structures/units design software integration development trends

Question:	**Do you agree with the following statement?**
Q1	Offshore structures/units design tools and software should develop into fully integrated packages with smooth interface between different disciplines/design tasks (e.g. structural, hydrodynamics, stability, shape development, etc.)
Q2	The focus of offshore structures/units design tools and software development should remain in the separate packages (e.g. structural, hydrodynamics, stability, shape development, etc.).
Q3	More commercial tools/software should be developed regarding integration of different packages (e.g. structural, hydrodynamics, stability, shape development, etc.) vs. in-house developed solutions.

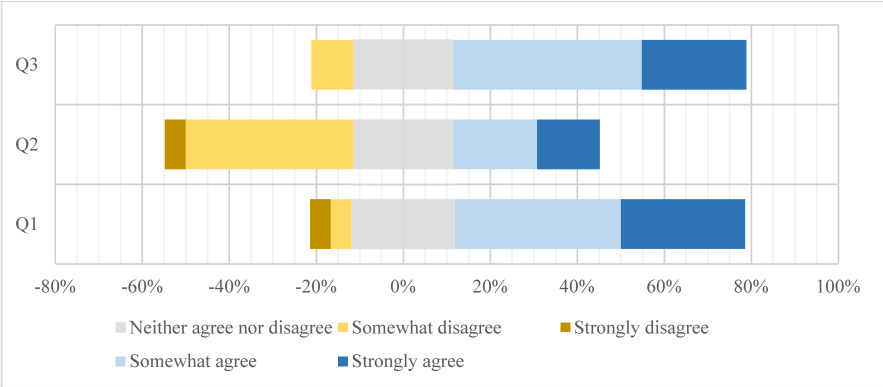

Figure 16: Offshore structures/units design software integration development trends

It is quite interesting when one compares the opinions about where tool development should focus with respect integration and interfacing to the somewhat low usage of integrated naval architecture packages reported earlier (refer to 0). It looks as though that more than advocating for the development of one-stop-shop type of tools, like integrated naval architecture suites, companies involved in the design of offshore structures/units tend to see the need to place effort in developing smooth integration between the different packages/tools. This is somewhat expected as integration and interface between different disciplines and related tools is known fact and a reported as a recurring issue. This also explains the agreement with having commercial tools developing smooth integration features rather than having companies engaging in such time consuming tasks and in turn removing focus from their main task of actually designing offshore structures/units.

A small percentage of respondents have indicated to use virtual reality tools aiding the design process (Table 7), and in fact it appears this technology is predominantly used for marketing purposes. It is however noted that virtual reality tools have been reported to be used for design review and interference check purposes. It is difficult to draw conclusions on the trend usage of virtual reality tools in or as an aid to the design process given the small sample size of survey respondents and also due to the very limited number of respondents employing such techniques.

Table 7: Virtual reality tools usage

Are Virtual Reality (VR) tools used in the design process or as a marketing tool?	Yes: 14%	No: 86%
If yes, for which purpose?	**Tools used:**	
• Marketing; • Design review & interference checking.	• Autodesk 3DS Max • Intergraph	

4.5 Foresight in Offshore Structures Design

The “lower for longer” oil price environment is expected to remain as one the most significant design drivers concerning oil & gas offshore structures in the coming years. It is expected that the trend of design standardization, optimization and ensuing design for cost effectiveness will continue in the coming years and actually endure beyond the current downturn. In a short term oil & gas production and related structures design will get more attention than other areas of the oil & gas value chain. Interest in LNG structures and infrastructure solutions will continue to grow pushed by both economic and environmental reasons.

Notwithstanding oil & gas operators are starting to reconsider exploration efforts as the need to replenish hydrocarbon reserves starts to become more and more relevant. The restart of exploration activities is expected to initially take place in the North Sea and thus focused on harsh environment structures/units. Overall, the focus on cost effectiveness while considering innovative designs pursuing competitive differentiation will remain instrumental for designing exploration offshore structures/units in the future.

The growth of other offshore sectors is deemed to continue and with it the need for research, development and new designs and methods. Offshore renewables, mainly driven by wind energy, will continue to mature with floating wind solutions likely to take the driving seat in terms of research and development. Deep sea mining and offshore food farming (both fish and algae) will be the subject of attention over the coming years and research and development efforts are needed to effectively mature these industries to the next level. Energy and associated environmental considerations will also contribute to open sea farming gaining momentum noting, for instance, recent stated intent of kelp farming potential to replace up to 20% of fuel production in the US.

On the subject of production structures/units it is noteworthy to mention several points raised by de Beer (2017) such as the fact that corrosion and fatigue are still the number one problem in FPSOs needing as much attention as ever and hence making design for corrosion imperative. New inspection techniques using drones and other unmanned vehicles and design for such features were also indicated as a trend. The survey conducted by Haïdar (2016) also points towards this, results showing a growth in the use of new technologies for inspection and maintenance. As risk-based inspection gains solid ground there is a need for reliable damage development models; a need to study and establish criteria to judge current state of damage as well as criteria to judge criticality.

Another interesting design issue discussed by de Beer (2017) was the 10,000 year case that currently is being required by regulatory bodies as design case (commonly employed in air gap of semisubmersibles or TLP tendon compression assessment) for FPSOs structures though it should perhaps be treated as a survivability and robustness check. Similar cases of rules, regulations or specifications going beyond practical parameters and driving design and end cost past actual requirements are found for exploration units, e.g. recent classification rules for drillships have imposed 100-year design wave considerations for what are inherently mobile units that in reality avoid such harsh conditions. Another example are requirements set for the design of dynamically positioned units which historically and systematically result in over powered designs having power plants operated far from optimal with adverse effects fuel consumption and emissions. Solutions to these issues require collaboration to reach a common ground between all stakeholders in the industry and research and development is needed from owners, designers, regulatory bodies and academia alike.

The subject of treatment of abnormal (low probability) events in offshore structures design was also addressed by Morandi (2017) and adding the challenge of how to deal with these in the advent of digitalization and big data. The author mentioned stochastic finite element analysis is not being used to the expected extent in offshore structures design, especially compared with other industries; and the need to effectively consider area statistics versus single point statistics in the design of offshore structures.

In both aforementioned keynote lectures a call of attention was made by presenting examples that highlighted the lack of attention to engineering first principles by young engineers. In fact, this opinion is shared by a large extent of the veteran community in the offshore industry. While it is generally acknowledged that the use of computer tools is essential in the design of structures/units, solid knowledge and understanding of the basics is fundamental to properly make use of the available technology. Academia should, in its educational tasks, thus make an effort to generate graduates with well-balanced knowledge of first principles and computer tools and methods.

Digitalization, big data and automation issues are expected to gain much interest in the near future. Already with many ongoing pilot projects and successful applications to asset integrity and maintenance management as well as operational optimization, it is believed that this technology will leap into design as noted by Wiley (2015) discussing a single software solution for design, operations and optimization. It is foreseeable that the industry will make use of the enormous potential of utilizing data from existing and operating units to reconsider design assumptions and ultimately leading to technically and commercially optimized solutions.

Computer aided design and tools are key to the offshore structures design process which relies heavily on direct calculations, more so than in the case of commercial ship design. From the survey conducted by the Committee one can identify that software integration is still an important issue as communication and translation of data between different packages is still consuming a considerable amount of time in the design process. More than having one tool fitting all trades, the industry would benefit from development towards seamless integration and communication between the existing tools.

5. STATE-OF-ART VS. STATE-OF PRACTICE

5.1 Motivation, background, and aim

State-of-the-art vs. state-of-practice is a new theme into the ISSC IV.2 committee's work in order to initiate the discussion and bridge the gap in between the research work presented within the committee's remit and the practical applications that may stem of it. The above was initially highlighted by Prof. Moan acting as official discusser of the ISSC 2015 Committee IV.2 Design methods report (Moan, 2015). The above distinction in between state-of-the-art vs. state-of-practice research refers to design methodology that will improve the practical design approach, optimization tools implemented in practice and new knowledge provided through research papers related to current practices in monitoring and inspections especially of hull structures. Prof. Moan referred to one of the key ISSC Committees' tasks *"...to identify knowledge resulting from research which is novel, validated and relevant for use by the industry and regulatory bodies. It is important that the Committee highlight the papers of greatest potential value for the users*". In particular, he addressed the status of reliability–based design in practice as well as the most significant R&D results in terms of industrial application.

A quick look through Oxford dictionary suggests that the term "state-of-practice" unlike the term "state-of-the-art" is not fully defined. Taking into account that "practice" is the actual application or use of an idea, belief, or method, as opposed to theory related to it, the "state-of-practice" definition will provide an indication of the best design process which will be also integrated with production, maintenance and repair available in everyday engineering systems.

In this respect, a common approach that is often used to access information related to state-of-practice related engineering applications is the use of questionnaires distributed to industrial stakeholders. This approach was employed by Committees IV.1 and IV.2 within their ISSC2003 report (ISSC2003, 2003). The questionnaire of Committee IV.1 addressed the use of systems engineering methods and general trends stemming from it resulting in twelve responses being received from different organizations and countries of origin. On the other hand, Committee IV.2 used a questionnaire-based survey to collect information related to the actual use of IT systems within shipyards and also examine the expected improvements based on practical IT applications. In this case a higher response rate was observed including 17 questionnaires returned by a large range of shipyards located in Asia and Europe (ranging from SMEs to big shipyards, employing from 60 up to 11,000 employees).

In its ISSC2012 report, Committee IV.2 decided to distribute a web-based survey among shipbuilding stakeholders concerning IT tools and data exchange applications (ISSC2012, 2012). Target audience of this survey included shipyards, design offices, research centres, software vendors as well as universities. In this case, the Committee report included feedback from 23 stakeholders which were deemed insufficient to draw specific conclusions; however provided a representative body of information good enough to analyze and suggest the application trends within the shipbuilding industry. One of the main conclusions reached was that more effort is required with regards to better integration of data originating from the initial design stages to the final disposal phase of ship life cycle. Having in mind all the knowledge and results stemming from the previous Committee efforts and reports, Committee IV.2 applied a quantitative analysis[1] approach in order to provide a thorough and as complete as possible picture of the trends in the design methods industrial applications.

5.2 State-of-the-art

5.2.1 Bibliometrics

According to Pendlebury (2008), bibliometrics (sometimes called scientometrics) turns the main tool of science, quantitative analysis, on itself. This approach is widely used by universities, policymakers, information specialists and librarians, and researchers themselves for quantitative evaluation of publication and citation data to analyze the level of R&D.

The Organization for Economic Co-operation and Development (OECD) Report (OECD, 2015) presents the actual level of technology and innovation for growth. One of the conclusions in the report is that an increasing gap between basic research and the development of new products and processes exists (Figure 17). Although the applied research and experimental development efforts have more than doubled since 1985, they remain well below the amount of basic research. Another significant indication is the continuous growth of the amount of basic research over the years. The latter is also supported by a study performed by the University of Ottawa stating that approximately 2.5 million new scientific papers are published each year (University of Ottawa, 2017).

In this respect, in the bibliometrics numbers provide the following information: papers in indexed journals; papers per year on average; papers in top journals (various definitions); number of total citations and number of relative ones i.e. citations per paper compared with citations per paper in the field over the same period; citations vs. expected citations; percentage of papers cited vs. uncited compared to field average; rank within field or among peer group by papers, number of citations, or number of citations per paper (Pendlebury, 2008)

The implementation of bibliometrics in the following sections is based on the following assumptions:

- The number of reviewed papers is a testimony to the interest of researchers and practitioners in a relevant engineering field;
- The ISSC Committee includes experts from all over the world and thus provides a broad basis for reviewing the publications;
- The Committee members have extensive experience that helps them to highlight significant publications and provide further insight into the subject matter.

[1] "If you can measure that of which you speak, and can express it by a number, you know something of your subject; but if you cannot measure it, your knowledge is meager and unsatisfactory." William Thomson, Lord Kelvin

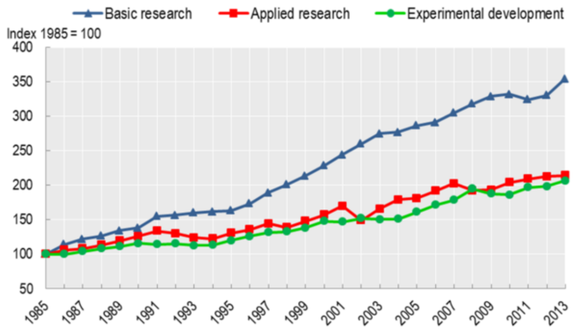

Figure 17: Trends in basic and applied research and experimental development in the OECD area, 1985-2013 (OECD, 2015). Note: *Constant price index (USD PPPs 1985 = 100). The index has been estimated by chain-linking year-on-year growth rates that are calculated on a variable pool of countries for which balanced data are available in consecutive years and no breaks in series apply*.

5.2.2 Main research topics and their bibliometrics

In order to have a structured approach into identifying the main research topics of interest and their bibliometrics, the current Committee IV.2 members analyzed the main committee topics addressed during the last three Congresses (period 2006-2015) also including the ones suggested for inclusion in the 2018 report. This resulted in identifying the most common topics and areas of interest including sub-sections mentioned in at least of three of the reports (Fig. 18). As can be observed, the most frequently mentioned sub-sections are related to: Design methodology (DM); Design tools (DT): Optimization developments (OPT); and Life Cycle Management (LCM). In some cases, there is no clear distinction in between some of the formulated topics addressed within the papers, e.g. there are papers discussing on the design tools particularly developed for LCM while some other papers consider the optimization of lifecycle costing.

Sub Chapter	ISSC2009 Seoul KOREA	ISSC2012 Rostock GERMANY	ISSC2015 Lisbon PORTUGAL	ISSC2018 Liege – BELGIUM & Delft – The NETHERLANDS
1	Design and production processes	Design for Life Cycle	Design methodology	Design methods
2	Information technology	Available Design Methods	Design tools	Design tool development
3	Maintenance and repair	Available Modelling and Analysis Tools	Optimization developments	Offshore Structures
4	Multi-criteria and multi-stakeholder optimization	Optimization and Decision Support Tools	Classification society software review	State-of-art vs. State-of-practice
5	Recent design tool developments	Product Lifecycle Data Management	Structural lifecycle management	Comparison of Classification Society software
6				Lifecycle data management
Period	2005-2008	2008-2011	2011-2014	2014-2017

Figure 18: Main research topics in the Committee IV.2 reports during the last four ISSC Congresses

Moreover, the sub-section on “Maintenance and repair” addressed within the ISSC 2009 report (ISSC2009, 2009) was incorporated in “Product Lifecycle Data Management” at the next Congress. In more recent developments, there is no specific sub-section on IT implementation mentioned after the ISSC 2009 report as this is nowadays used in a number of different applications and is covered within other sub-sections. The focus on Class software mentioned at the ISSC2015 report was appreciated as a good step forward and was deemed necessary to further incorporate it in the following Committee report as well. The new chapter of ISSC2018 Congress “Offshore structures” includes a review of papers in design methodology in offshore structures design and the number of them is included in topic DM (DMoff). Similarly, the number of papers in subchapter “Asset Integrity & Maintenance” is taken into account in LCM (LCMoff).

Summarizing the above, the number of reviewed papers in the four thematic areas of the last four ISSC is presented in Figure 18. Furthermore, Figures 19-20 present the number of papers by year of publication for the mentioned topics.

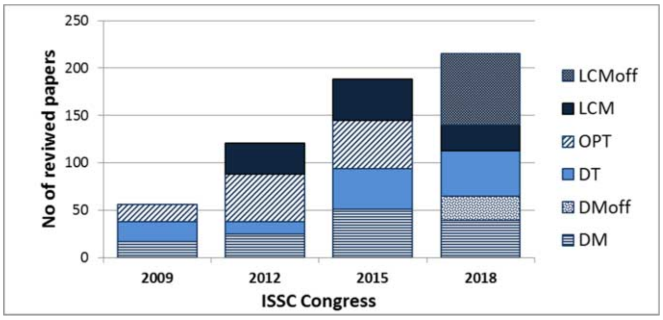

Figure 19: Number of reviewed papers in Committee IV.2 pre topic over the years

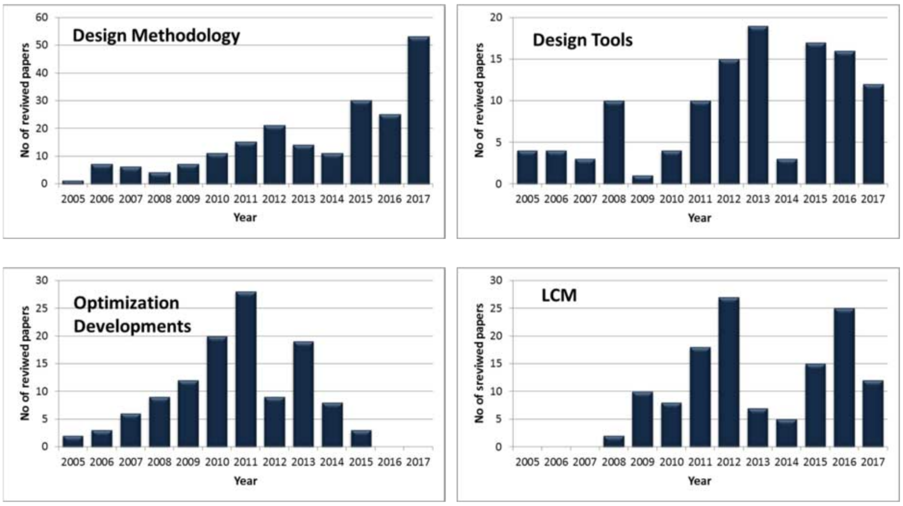

Figure 20: Number of reviewed papers of the selected research topics in relation to the year of publication

From the graphs shown above, the following conclusions can be derived:

- There is a steady increase in the total number of papers reviewed within ISSC IV.2 Committee "Design methods", which coincides with the general tendency of increasing scientific publications over the years. This number has been almost 4 times larger for the past 10 years;
- The number of considered papers over the years for the topics is cyclical. The maximum is followed by a reduced number of papers in all of the topics.
- The information shown above validates the Committee suggestions to re-organise the structure of some of the report sections. For example, one of the Committee's first suggestions was to have no dedicated sub-section on optimization developments in ISSC 2018 report. Instead it was suggested to include the implementation of optimization techniques as a sub-section within the "Design tools" main section;
- The number of papers published at the year before or after the Congress is smaller according to the presented statistics (it is clear for 2014 for DT). One reason for this could be the closure of the report almost a year before the congress, and not the consideration of the last year publications by the next committee. This should be taken into account in the work of all ISSC Committees.

The next sections give a brief description of the main topics highlighted during the past congresses in the above specified scientific fields. In this respect, the information provided below is a summary of the information presented in other sections of this Chapter and will rather provide general information about the research focus over the years and main conclusions drawn; therefore, there will be no specific reference to material already presented elsewhere. Such review and the conclusions from the present report will provide the reader with valuable information on topics that researchers have been focusing on over more than the past 10 years.

5.2.3 Design methodology

The main focus of the papers concerning design methodology during the ISSC 2009 report is related to the development of 3D CAD applications based on NURBS methodology (that is the standard approach today) and implementation in production process. Key advantages of the development of 3D CAD models are related to the improvement of production by generating production material information, simulating preconstruction, speeding up data modification time, and erection planning. The developed methodology and supporting tools allows users to easily generate the hull structural model at the initial design stage. Such 3D model permits the generation of a finite element representation of ship's structure. The studies focus on the application of a single NURBS surface representing a sea-going ship hull, to create developable surfaces and describing a hull fairing process based on the use of a NURBS ruled surface method (Cross-Fix Method).

In order to prevent distortion and to improve the quality during construction of the ship a methodology for the use of Transient Thermal Tensioning (TTT) is suggested. The first tests showed eliminating of the buckling at 5 mm plate after the implementation of TTT. The main themes of research in design methodology in the period 2008-2011 were better described as *Design for X* approach and rationality and probabilistic modelling. It was acknowledged that the systems approach made a deep impact on ship design methodology and can be used as a common platform for new developments and innovative design techniques.

Today ship design is also highly integrated with other design development activities, such as production, costing, quality control, among others. At the same time essential parts of the modern shipbuilding industry are environmental concerns, safety, passenger comfort, and life-cycle issues. Within this paradigm shift, the new designs should facilitate the productivity sequence, be cost-effective, incorporate aspects related to safety and environmental considerations while also being functionally efficient.

The review of ISSC 2012 report concluded that many “Design for X” (DfX) processes have been developed in order to correct the inadequacies of the designs during the ship initial design stages. Shortly DfX is defined as “… *process of pro-actively designing products to optimize all the functions throughout the life of the product*…” (ISSC2012, 2012). So “Design for X” can incorporate various aspects including among others Design for Production, Design for Manufacturing, Design for Assembly, Design to Cost, Design for Simplicity, Design for Maintenance, Design for environment, Design for Safety, Design for Life Cycle Cost, Design for Robustness, and Design for Six Sigma.

Economy together with safety and environmental protection remains the most essential goal of commercial ship design. Ship safety is essential as economic objectives too. This concerns the following aspects: safety of human lives, the risks of damage to or loss of ship and cargo, and the hazards to the environment. Some of the most important results of this research effort are also related to the quantification of risks at the early design stage.

Moreover, several Formal Safety Assessment (FSA) studies have been developed in the framework of EU funded SAFEDOR project that supported the IMO MSC associated work. The FSA methodology helps also the Classification Societies to develop risk-based acceptance criteria for their own rules. During the same period pioneering work has made random processes amenable to probabilistic modelling such as the irregular seaway and ship collisions and groundings. An example of the above is the compartmentation of double hull tankers, optimization, design optimization and structural reliability. In the implementation of CAD external and in-house interfaces remain heterogeneous. The conclusion is that larger scale integration is not yet fully realized. The ISSC 2015 report also highlighted the development of the “Design for X” approach. In this case the most relevant DfX aspects from structural design point-of-view are the design-for-production and design-for-safety. In general, DfX's concept places emphasis on the performance achievement, and is closely related to the goal-based design methodologies in general and risk-based design in particular. In this regard, IMO and the International Association of Classification Societies (IACS) decided to move from prescriptive concepts to probabilistic assessment methods and Goal-Based Standards (GBS). The ISSC 2015 report (ISSC2015, 2015) emphasised on the challenge to transfer from rules-based to risk-based design. The concluding by suggesting that the implementation of the risk-based design in ship design requires considerable time and effort.

One third of the reviewed papers in the ship design methodology section are related to the developments in ship form-function mapping and corresponding search in the defined design space. In this case, the design is considered as a mapping process from the function space that defines needs and requirements, to a form space containing the description of the final design. To support the mapping process there are several competing strategies i.e. set-based search strategies or using knowledge-based systems in the design process.

The main tool employed in this form-to-function mapping is the analysis methods tool that allows for a fast and efficient evaluation of specific design alternatives as part of an overall design process. The wide adoption of CFD and FEA tools has contributed to a tendency towards implementation of high fidelity models in the early ship design stages. To alleviate this, two approaches are considered. The first one is a more efficient, seamless integration of high fidelity tools into CAD software; the second one is related to a more efficient search through the design space by updating key empirical methods or by applying surrogate modelling. A slightly different approach to using simulation for analyzing system performance is performed by using discrete event models such as metocean, fleet logistics, and ice ones that capture the complex operation of a ship. Such an approach provides a more detailed and realistic representation of the operational profile of the vessel as opposed to idealized design cases.

5.2.4 Design tools

In most cases design tools are related to solving optimization tasks, thus it is challenging to separately consider them. The ISSC 2009 committee report highlighted the use of the Hybrid Co-evolution based multi-objective Particle Swarm Optimization (HCPSO) tool. The tool combines co-evolution, game theory and extremum analysis to develop an effective optimization approach. In this respect, three topics are reviewed: CAD/CAE systems; design tools for production and cost and design considerations for fire and smoke.

As a typical feature in CAD/CAE implementation, the use of graphic tools (AutoCAD, Microstation, etc.) to finalize the classifications drawings and other software codes is performed. This approach provides the opportunity to easily write-out customized macros and generate a topological and parametric structural model (NAPA, NAPASteel). The main conclusion is that the design tool together with producing a structural model should be able to extract the classification drawing and to generate an FEM model to be processed by the most common dedicated codes.

In order to withstand the competition, the shipyards must be able to accurately assess costs. In this case, the methods for estimating production costs are classified into two groups: top-down and bottom-up approaches. The top-down approach determines the production cost from global ship parameters i.e. ship type, main dimensions, weight of the hull, the block coefficient, ship area etc. The bottom-up, approach is based on automatic extraction and identification of structural features, such as cut-outs, weld lines, and bevels, from CAD/CAM data. Fire is also a hazard that can be highly complex, thus the ISSC 2015 report highlights research related to fire simulation. The final conclusion is that the coupling of design, evacuation and structural software could provide a substantial area of research for the next decade.

The state of development of tools for the design of marine structures of the ISSC 2012 report is characterized by increased scope, integration and transfer of advanced analysis tools into the early stages of ship design. Three groups of tools are reviewed i.e., naval architecture packages; specialized and general purposes CAD systems and tools to manage inventory of hazardous material data. The report provided information on naval architecture software packages for relatively simple calculations of hydrostatics to advanced packages employed for the analysis of ship performance aspects. The following general purpose CAD systems were considered: CATIA; CADDS5; AVEVA; ShipConstructor; FORAN; Paramarine; Inteliship; Nupas-Cadmatic.

A good example of a software package that follows the requirements of international convention for the "Safe and Environmentally Sound Recycling of Ships" concerning the hazardous material data is the PrimeShip-Inventory provided by ClassNK. The ISSC 2012 report also included a survey of the current practice that was mentioned above. The survey included a questionnaire on the implementation of CAD tools, Class Society tools, general purpose structural analysis tools and CFD tools.

The review of the research in the area of design tools of the ISSC 2015 report was focused on the following topics: further development of the tools; tools for lifecycle cost modelling; links between design tools and production and operational phases. A review of software developed by Classification Societies was provided. Software provided by ten Classification Societies was compared and capabilities of approximately eighty types of software tools and applications were described. The tools were divided in two main categories: tools for the assessment process of the ship structure and tools for the Project Lifecycle Management (PLM). No benchmark study was performed but the evaluation was carried out answering a number of key questions. Common for all software tools was the increased use of 3D FEA, on-line collaboration and extension of data/model usage throughout the ship lifecycle.

Extensive development in linking multiple tools in order to conduct a more comprehensive structural evaluation of new ships and offshore structures were reported. A particularly active area was the one linking the output of either 3D potential flow codes or CFD codes to FEA. Much work was also focused on code linking and automation and the development of stand-alone structural design tools. Concerning the lifecycle assessment (LCA) the conclusion was that much work remains to be done to move LCA into a practical method for vessels under construction.

5.2.5 Optimization developments

The contribution and considerable progress to the optimization developments during the ISSC 2009 committee work and considerable progress in the field is are related to the EU funded project IMPROVE (2006-2009). The project objective was to deliver an integrated decision support system for a methodological assessment of ship design so as to provide a rational basis for making decisions pertaining to the design, production and operation of three new ship generations (LNG, ROPAX and Chemical Tanker) by applying the novel Multi-Stakeholder Design (MSD) approach. As a result, the generated design alternatives demonstrated the following potential improvements: increased carrying capacity; decreased steel and production cost; increased safety measures via the rational distribution of material and improved operational performance and efficiency, including a benefit on maintenance costs for structure and machinery, and reduced fuel consumption.

The project did not develop new mathematical optimization methods but integrated existing Design Support Systems (DSS) in the design process. Four optimization packages were considered as follows: LBR5 - for optimization of ship structures at the conceptual design stage in terms of cost, weight and stiffness; MAESTRO – the software combines rapid ship-oriented structural modelling, large scale global and fine mesh FE analysis structural failure evaluation; scantlings and topology optimization; OCTOPUS – for simplified FEM response calculations at concept design phase, ultimate strength and system reliability evaluations combined with a set of optimization solvers; CONSTRUCT – for structural assessment and optimization of ship structures in the early design stage of ships. The software applies the Coupled Beams method for evaluation of the structural response and the fundamental failure criteria.

The Multi-disciplinary Design and Optimization (MDO) system consists of the synthesis design method for several ship subsystems i.e. hull form definition and optimization; seakeeping; structural design optimization; general and cargo arrangement design and optimization; propulsion machinery sub-systems design; local sub-systems such as- outfit, electrics and handling systems. Due to the high computational expense of such analyses, approximation methods such as design of experiments combined with response surface models are used. Since the approximation model acts as a surrogate for the original code, it is often referred to be a surrogate model or metamodel (i.e. a “model of a model”). A variety of approximation models exist including polynomial response surfaces, kriging models, radial basis functions, neural networks and multivariate adaptive regression splines.

The focus in the overview of the tools which led to the ISSC 2012 committee report is related to large scale optimization techniques, i.e. surrogate modelling, decomposition and coordination. The selection of appropriate surrogate method depends mostly on the characteristic of physical phenomenon that is approximated. Multi-disciplinary optimization methods require decomposition of the problem into individual optimization problems that are coupled. Some of the existing coordination methods include: Optimization by Linear Decomposition (OLD), Concurrent Subspace Optimization (CSSO), Collaborative Optimization (CO), Bi-level Integrated Systems Synthesis (BLISS) etc.

The optimization developments are broadly discussed in the ISSC 2015 committee report by referring to the Design Support Systems (DeSS). The overall design procedure, including the optimization utility is composed of three main steps: design problem identification, design problem formulation, and design problem solution. Although, there is no new approach proposed since 2011 the report presented summary of research and application of optimization for ships and offshore structures. Important subsets of the overall optimization problem are optimization for production and optimization for lifecycle costing. The application of optimization methods has been examined in the light of achievements in parallel processing and hardware developments and implementation of surrogate modelling and variable fidelity approaches.

5.2.6 Life cycle management

The challenges related to ship life cycle are initially considered in the ISSC 2012 Committee IV.2 report. An extensive review was presented in two subchapters: Design for life cycle and Product lifecycle data management. In the first subchapter the Committee report presented the achievements in the following topics: integrated life cycle management; design loop and lifecycle data management; and drivers for integrated life cycle management. The second subchapter highlighted the state-of the art and current practice in Product Lifecycle Management (PLM). The final conclusion of the ISSC 2012 report was that the maritime industry has not yet routinely applied robust PLM solutions for design and operation of vessels.

In addition to the above, the chapter of the ISSC 2015 report on "Structural lifecycle management" contained four sections: Tool Development, Data Interchange and Standards, Integration with Repair, and Integration with Structural Health Monitoring Systems. The report summarized the outcomes of this section suggesting the vital role of an integrated lifecycle system that connects the overall design process with other operational parameters such as repairs and maintenance. Further to the latter, challenges related to the above is the application of such methodology on a full ship/marine environment. An accurate assessment of the increased performance and benefits to the vessel's structure was not possible at that time due to the lack of full-scale testing of such a system.

5.3 State-of-practice

Connecting research and practice has always been a challenging task. The continuous updated research literature needs to include practical applications. Mohram and Lawler III (2011) define three rationales for closing the gap between research and practice. These are related to instrumental and pragmatic arguments; values- based positions, and methodological and epistemological arguments.

Instrumental and pragmatic arguments postulate that it is a common interest to researchers and practitioners to close the relevance gap. Values-based arguments are connected to the views of researchers about: how they spend their time; responsibility to ensure that knowledge reaches practitioners; their criteria for good research and the topics they research. The last rationale involves the view that valuable knowledge can only be created when there is a close connection between research and practice.

The most important methodologies for connecting research to practice according to Mohram and Lawler III (2011) are:

- *Participation and collaboration*; including four approaches: basic research (that is informed by knowledge from other stakeholders); collaborative research; design/evaluation research (that entails eliciting and studying new designs and practices) and action/intervention research (that is generating knowledge in the process of solving the problem of a particular client);
- *Knowledge combination*; Combining theoretical knowledge from different disciplines with knowledge from practice when trying to understand a complex problem;
- *Studying problems in context*; Whereas researchers tend to ignore or to control the information that is relevant to an understanding of the text the practitioners look for contextual similarity to determine whether knowledge from research can be applied in their setting;

- *More prediction, less retrospection*; Researchers often employ methodologies to find out what patterns of relationships currently exist, rather than what would happen if the organization changed the way it operated.

Beyond this theoretical insight into the link between research and practice, the following sections shortly describe practical approaches that can assist with the work of the ISSC Committees to close the loop between research and practice, particularly referring to the Technology Readiness Levels.

5.3.1 Technology Readiness Level - TRL

The development and introduction of Technology Readiness Levels (TRL) is a method of estimating technology maturity of a research program during the acquisition process. TRL were originally suggested by NASA in 1974 and formally defined in 1989 and eventually adopted in 1990 introducing a 9 scale level (Banke, 2010). There are different definitions available but these are conceptually similar. Some differences though exist in terms of maturity at a given technology readiness level. Table 8 compares the NASA and European Commission (EC) suggested definitions (EC 2017). The aim in this case is to use the TRL distinction to provide suggestions on which type of research project proposals should be funded aiming at a minimum TRL threshold and also used in evaluation of the mentioned research proposals.

Table 8: Comparison of the NASA and EC TRL definitions

TRL	NASA Definition	EC (HORIZON 2020) definition
1	Basic principles observed and reported	Basic principles observed
2	Technology concept and/or application formulated	Technology concept formulated
3	Analytical and experimental critical function and/or characteristic proof of concept	Experimental proof of concept
4	Component and/or breadboard validation in laboratory environment	Technology validated in lab
5	Component and/or breadboard validation in relevant environment	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in a space environment	System prototype demonstration in operational environment
8	Actual system completed and 'flight qualified' through test and demonstration (ground or space)	System complete and qualified
9	Actual system 'flight proven' through successful mission operations	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The European Association of Research and Technology Organizations (EARTO) also suggests a thorough and structured TRL scale as a research & innovation policy tool (EARTO, 2014). In their report, EARTO indicates some limitations of the use of TRL scale as follows:

- Lack of attention to setbacks in technology maturity – the higher TRL levels also requires additional research;
- Single technology maturity approach – the limitation is connected with the focus on a single technology;
- Focus on product development rather than manufacturability, commercialization and organizational changes – non-technological aspects like readiness of an innovation to go to market or the readiness of an organization to implement the innovation, are not taken into account;
- Context specificity of TRL scales – i.e. the scale needs to be adapted to the specific purposes of the organization.

In this respect, EARTO provides a further description of the TRL scale included in Annex 1 (EARTO, 2014), a summary of which is presented in Figure 21

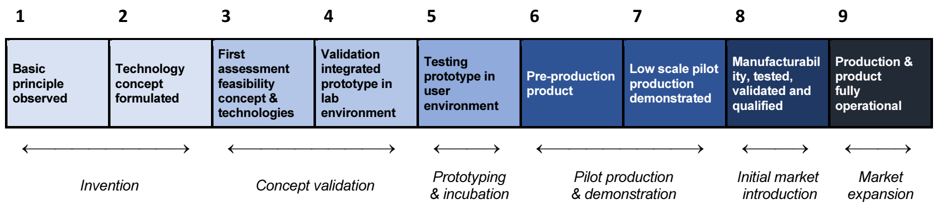

Figure 21: EARTO description of TRL scale (adopted from (EARTO, 2014)

Following the above, the US Transportation Research Board (TRB) also suggested the notion of practice-ready papers. TRB is one of six major divisions of the US National Research Council, which serves as an independent adviser to the federal government and others on scientific and technical questions of national importance, and which is jointly administered by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The standing committees in the TRB Design and Construction Group have been identifying and cataloguing practice-ready papers since 1998.

A practice-ready paper is a paper in which the research results presented and discussed make a contribution to the solution of current or future transportation problems or issues for practitioners. To nominate a practice-ready paper there are several guidelines:

- The paper must be recommended for presentation at the Annual TRB Meeting. (Publication in the Transportation Research Record is not a requirement.);
- The research results presented and discussed in the paper should be ready for immediate implementation or with minimal additional research or implementation effort;
- The paper should contain guidance on additional effort required for implementation;
- The research should make a major contribution to the solution of current or future problems or issues;
- Benefits that can be derived from implementation of the research should be evident - for example, cost savings, increased safety, or improved environmental impact.

In 2010, TRB automated the process of finding practice-ready papers by launching its Practice-Ready Papers (PRP) database (US TRB 2017).

5.3.2 ISSC IV.2 Committee point of view

Driven by an understanding of the extremely important link between research and practice while also considering all the previous approaches and work performed by previous Committees, the current ISSC "Design methods" Committee moves forward to reduce the gap between research and practice. The main purpose of the suggested proposal is to identify in a reliable and structured way research papers and relevant literature, which can lead to potential high impact applications of mentioned research, particularly applicable within the context of the ISSC Committees' work. In this respect, the suggestion for Theory to Practice Ready Papers (TPRP) approach can be formalized as follows:

- Development of a roadmap for proper organizing and conducting research quickly reaching practical applicability and corresponding presentation in the field of interest e.g. ship and offshore structures and associated systems;
- Formulation of guidelines for nomination and evaluation of TPRP.

Table 9 briefly presents the Committee suggestion for the levels of preparation for a TPRP by analogy to the Technology Readiness Levels described above.

Table 9: ISSC IV.2 suggested levels of Theory-to-Practice-Ready Papers (TPRP)

TPRP	Level title	Level description
1	Critical review of existing literature	Initial level of readiness, state-of-the-art publication
2	Methodology outline	Knowledge acquired from existing literature is transformed into novel research and development
3	Feasibility study	Feasibility of the methodology suggested at TRL 2 is evaluated
4	Methodology elaborated	Methodology outlined at TRL 2 is now fully elaborated
5	Lab/simulated case study validation	TRL 4 methodology tested through a simulated case study or at lab conditions
6	Small scale case study validation	TRL 5 methodology tested through a real-data small scale case study
7	Full-scale deployment	Practice-ready research deployed at full-scale

The levels correspond to organizing and conducting independent research by a separate author/s or scientific institution, according to a topic that will have direct/indirect relevance to an industrial assignment and will eventually lead to high industrial impact. Although this is a first effort in such a direction, which also needs to be followed by a more analytical investigation to provide further details, it can provide a draft guide streamlined to fir the ISSC Committees work.

Further to the above TPRP scale, more details on the above can be provided as part of the following ISSC Committee work. The results and agreed TPRP papers and relevant literature can be presented during the next Congress. A further suggestion would be for each ISSC Committee to elaborate and evaluate potential papers, which can be appropriate for using within the suggested TPRP approach.

6. COMPARISON OF CLASSIFICATION SOCIETY SOFTWARE

6.1 Introduction

Over the last few years, Classification-Societies (CS) have provided ship designers and surveyors with software tools to evaluate the scantlings of ship's structures. The report of the IV.2 – Design Methods Technical Committee (TC) presented at ISSC2000 provides a first overview of the CS tools and defines a set of criteria for the analysis and categorization of these software packages. The growth on the supply of CS software tools and their development over the previous 15 years, were the driver of a study conducted by the IV.2 – Design Methods TC of ISSC 2015 IV.2. The study built on the previous TC's report and extended the survey to 10 major CS, including tools and functionalities which support ship designers and surveyors from the early design stage, towards the entire ship life.

Since the software packages reviewed in ISSC 2015 were strictly related to the specific rules of the classification societies who developed them, direct comparison was not immediate. In this scenario the issue of IACS Common Structural Rules introducing a set of regulation recognized by all IACS's CS, presents an interesting updating also from this point of view.

6.2 The IACS Common Structural Rules

The IACS Common Structural Rules (IACS 2006a, 2006b), issued in April 2006, were developed as separate rule sets:

- IACS Common Structural Rules for Double Hull Oil Tankers (CSR-OT)
- IACS Common Structural Rules for Bulk Carriers (CSR-BC)

While maintaining prescriptive requirements based on experience, these rules extended the use of the Direct Strength Analysis (DSA) in ship's structural design, introducing complex scantling evaluation formulae, and increasing the load cases to be verified for the local scantling, often explicitly requiring Finite Element Analysis (FEA). Aided design CS tools immediately became necessary, with the growing demand by surveyors and designers of specific tools which are able to ensure the robustness of the required analysis and the correctness of the analysis outcomes, reducing at the same time the engineering time and cost.

The two rule sets of the IACS-CSR prescribed two different methodologies to be applied to oil tankers and bulk carriers, even in some fundamental technical matters which should be commonly treated for all types of ships. This was an important issue from the perspective of shipyards and designers involved in ship structural designs (Shibasaki, 2016). The harmonization of these two rule sets was IACS' resulting activity, and CSR-OT and CSR-BC were superseded by the new unified Common Structural Rules for Bulk Carrier and Oil Tankers (CSR BC & OT), referred as Harmonized CSR, H-CSR or CSR-H, issued on 1st January 2014 and entered into force on 1st July 2015.

As for the evaluation and assessment of the structural analysis results, it is a matter of course that the issue of the new H-CSR has increased ship designers work load regarding, for example, the number of loading conditions, numerical models, and parts and details to be analyzed. In this regard, each CS has developed its own software tool for the structural assessment according to the H-CSR and offers it to the shipbuilding industry and in particular to ship designers who are expected to use it to verify the compliance of the design with the rules. In other words, it is practically impossible to design oil tankers without the software tool provided by the CS. Therefore, today the cost of the structural design for shipyards is directly affected by the quality, convenience, functionality, efficiency, and accuracy of the software provided by CS (Shibasaki, 2016).

The new H-CSR not only replaced the separate rules for bulk carriers and oil tankers with harmonized rules but also introduced some new requirements. There are two major changes in H-CSR compared to the old CSR. The first is the prescriptive rule changes including load cases, minimum thickness, tank pressure and so on. The second is the extended scope of FEA including coarse mesh, fine mesh and fatigue analysis. A study on the design changes and weight increases due to the issue of the new prescriptive rules and the FEA of the whole cargo hold was conducted by Un-Chul Choi (2016). The report shows that the introduction of the H-CSR has resulted in the hull structure being strengthened due to yielding and fatigue in cargo hold region and that approximately two months more are required for the structural design of a new vessel when compared with the old CSR.

The experience gained with the application of the CSR moved most of the CS to develop dedicated tools before the entrance into force of the new rules. Since these tools apply common requirements, they have definitely become independent from the specific classification societies in charge of the classification of a new construction, and may be chosen by the designer considering the offered functionalities.

6.2.1 H-CSR rules requirements

The evaluation criteria defined in previous ISCC IV.2-Design Methods reports are generally applicable to all CS tools. On the other hand, being the requirements of H-CSR very specific, an efficient way to evaluate related software tools should start from a rule analysis, especially considering that these rules emphasize the work flow to be use by the designers for their correct applications.

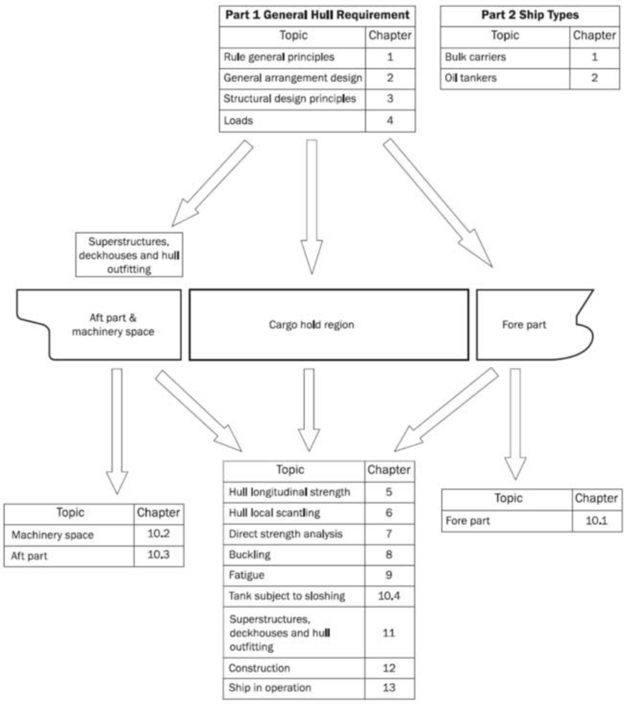

Figure 22: Application of the Rules CSR BC & OT (IACS 2017)

H-CSR are divided into two parts: Part 1 provides requirements common to all types of ships and Part 2 which adds specific regulations for each ship type (Oil tankers and Bulk Carriers). Each part's chapter refers to specific topics that can be also mapped considering the applicability region as described in Pt 1, Ch 1, Sec 1. [2.2.3]. Mapping of rules requirements are shown in Figure 22 (IACS CSR BC & OT).

It is also interesting to emphasize that, as per requirement Pt 1, Ch 1, Sec 1. [4.1.1] the designer should take care that the parts of the structure not covered by H-CSR rules are in compliance with the relevant requirements of CS's Rules. Requirements are divided as follows:

- Minimum requirements to be applied irrespective of all other requirements prescribing minimum thickness, independent to the specific minimum yield stress, and minimum stiffness and proportion, based on buckling failure modes;
- Load-capacity based requirements to assess structural members controlling one particular failure modes. In general Working Stress Design (WSD) method is applied in the requirements, except for the hull girder ultimate strength where Partial Safety Factor (PSF) method is applied. Summary of loading scenarios and corresponding rule requirements are presented in Pt 1, Ch 1, Sec 2. Table 1.

Structural response analysis is to be approached using Beam theory or FE analysis verifying acceptance criteria summarized in Pt 1, Ch 1, Sec 2 Table 2 and 3. Indication for the verification of compliance is given for both, new buildings, and ships in service.

H-CSR include also detailed requirements about structural arrangements, guiding the designer to a sort of standard project. In section Pt 1, Ch1, Sec 4 [3.7.1] an extended part is dedicated to structure nomenclature that could also be used to identify structural members and details subject to verification of compliance. Figure 22, abstracted from this section has been provided as an example. Table 11 in section 6.3.1 of this report, refers to a generic item "Prescriptive", introduced to give the evidence of software capabilities to support the assessments of these parts.

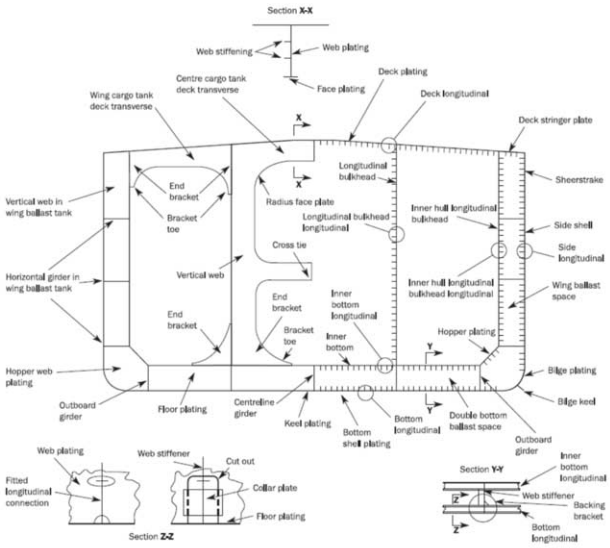

Figure 23: Mid cargo hold transverse section of double hull tanker (CSR BC & OT, IACS(2017))

Pt 1, Ch 4 relevant to loads is the most demanding part of rules in terms of computation time in particular when applied to direct analysis. Dynamic load cases, ship motion and acceleration, hull girder loads (wave and still water in intact and flooded condition), external and internal loads, are taken into account and combined as per requirements of Sec 2 of the same chapter.

Pt 1, Ch 7 is dedicated to Direct Strength analysis. Details are provided about meshing, properties input, loads applications, screening and results analysis for global, local fine and local very fine mesh models. Figure 24, abstracted from this chapter clearly show the flow chart of required assessments.

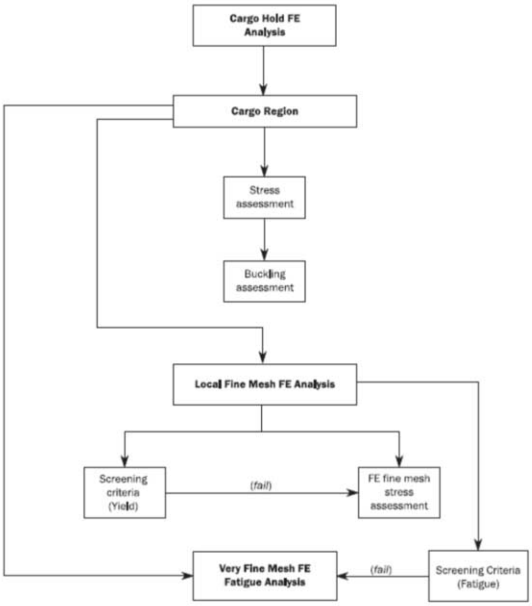

Figure 24: Flow diagram of finite element analysis (CSR BC & OT, IACS (2017))

The shipbuilding industry has recently started applying the H-CSR to the design of new tankers and bulk carriers. However, the substantial increased amount of FEA required by these rules created a big burden which impacted the structural design phase, mainly in terms of man hours and design cost for shipbuilders (Shibasaki, 2016).

Although H-CSR have been reviewed by the Industry, there are still some issues to be discussed for real ship design, especially for some new designs. Cai et al. (2016) presented the design of a new Aframax tanker designed to meet the requirements of new CSR. The authors performed the prescriptive calculation, and the direct strength analysis for the whole cargo holds, including yielding, buckling and fatigue. The impact of New CSR will be discussed as well as some technical issues, such as the shear force adjustment outside the cargo region, modeling and buckling evaluation of manhole region.

So et al. (2016) discussed the effect of H-CSR. The 50K class product carriers have been investigated and evaluated with H-CSR which was newly issued. From the investigation, there is not a great change in FE analysis. Certain methods have been introduced for FE analysis targeting outside midship region. Consequently, invisible areas for designer became much clearer than before. The main cause of the increased hull weight comes from the local scantling requirements such as minimum requirement, corrosion addition and change of loading sets, etc.

Study on Fatigue Strength for Tank Structures subject to H-CSR was report by Seo et al (2016), this report shows that detailed FE fatigue analysis for H-CSR and IACS Urgent Rule Change Proposal (URCP), and pointed out that there were locations the standard design recommended by H-CSR which should have sufficient fatigue strength did not comply with H-CSR fatigue requirement when FE fatigue analysis applied. And FE fatigue analysis based on URCP shows that fatigue life decreases up to 20%.

6.3 Comparison of classification society tools for H-CSR

As previously mentioned, a specialized software tool for structural assessment according to H-CSR is now essential in order to perform oil tankers and bulk carriers structural design and comply with the complex and extinguishable H-CSR requirement. Especially, not only ship designers but also CS surveyors are eager to use proper, usable and confident software tools. There are available a few H-CSR software tools which Classification Societies has recently developed and structural designers and surveyors has started to use. Hereinafter, the available H-CSR software tools are summarized and software functions of beginning design stage are briefly compared.

Bureau Veritas (BV), China Classification Society (CCS), American Bureau of Shipping (ABS) and Lloyds Register (LR), DNV-GL, Korean Register of Shipping (KR), and Nippon Kaiji Kyokai (ClassNK) have already released their own H-CSR software tools and are updating them in order to add new functionalities and fix bugs. This means that there are available 6 and more software packages.

Malcolm Latache (2017) reported that Common Structural Rule Software LLC (CSRS), which has been jointly developed by ABS and LR, and ClassNK have recently updated their own software tools to incorporate the new version of IACS H-CSR, which entered into force in July 2017. CSRS released version 2.5 of the CSR Prescriptive Analysis (PA) and CSR Finite Element Analysis (FEA) software. ClassNK released a new version of its software, PrimeShip-HULL (HCSR) Ver.4.0.0 incorporates the 2017 rule amendment. Latache also showed not only that these new versions of the software tools improved their user-friendly functions in order to support surveyors and designers. As reported in Table 10, also the other CS have updated and released new versions of the software tools that comply with the new version of H-CSR.

Table 10: CSR BC & OT Software updating according rule changes

CSR BC & OT Rule versions	BV	CCS	CSRS (ABS/LR)	DNVGL	KR	ClassNK
January 2015	✓	✓	✓	✓	✓	✓
Rule change 2017/07/01	✓	✓	✓	✓	✓	✓

Figure 25 shows the distribution of the present fleet of oil tankers with length equal to or greater than 150m and bulk carriers with length equal to or greater than 90m under survey of major IACS classification societies, and shows the number of ships (N) and gross register tonnage (GRT). Data have been provided by http://maritime.ihs.com/ and are updated to October 2017. Since H-CSR entered into force, there are not enough available data on the fleet under construction designed according new requirements. The presented charts consider the actual on-going ships and include in fact vessels non classified according CSR or H-CSR. The verification of data is out the scope of present work and the has been used only to suggest the actual trend which is expected to be also meaningful for the influence of IACS classification societies developed software in the near future.

6.3.1 H-CSR software packages

H-CSR software functionalities are summarized in Table 11 and Table 12. All the packages are suited to perform prescriptive rule calculation and direct strength analysis (DSA). All of them are already updated to the new H-CSR updated in July 2017. Data exchanges from/to CAD software packages are also considered.

As previously mentioned, H-CSR tools are able to perform two calculation phases, prescriptive rule calculation and direct stress analysis. The first phase is the calculation of structural scantlings according to rules requirement and 2-D analysis of the hull cross section. The second phase is 3-D Finite Element and DSA.

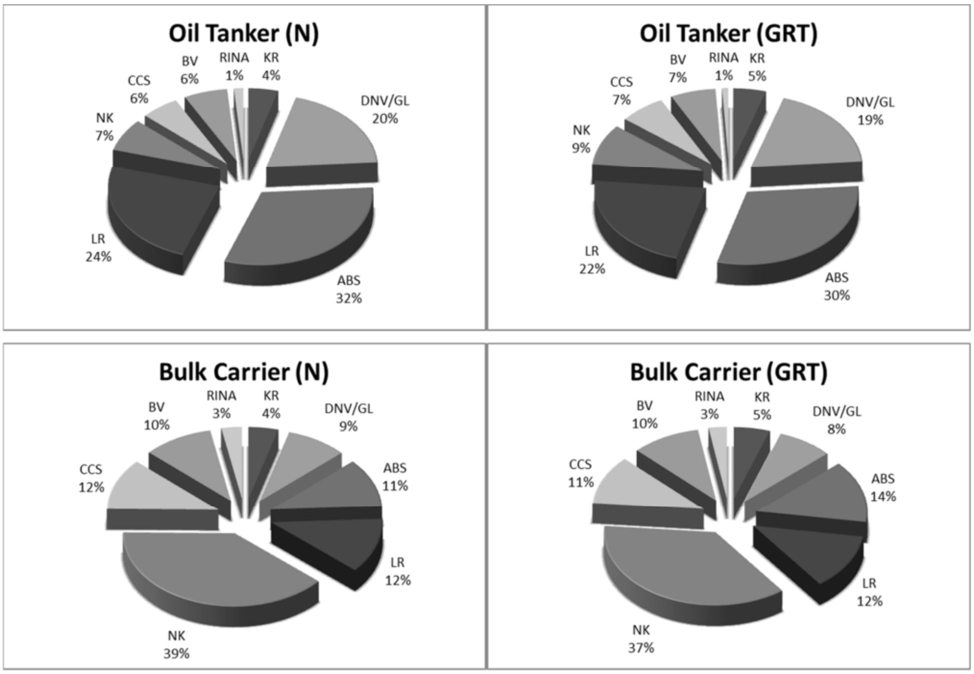

Figure 25: BC & OT under major classification societies survey

Table 11: Application and function matrix of classification software for H-CSR - Prescriptive

Prescriptive Rule Calculation Software		**BV**	**CCS**	**CSRS (ABS/LR)**	**DNVGL**	**KR**	**ClassNK**
		MARS	COMPASS CSR-SDP	CSR Prescriptive Analysis	Nauticus Hull	SeaTrust-HullScan	PrimeShip-HULL (HCSR) /Rules
Componets covered	Mid hold	✓	✓	✓	✓	✓	✓
	Fore/aft hold	✓	✓	✓	✓	✓	✓
	Bow/engine room/stern	✓	✓	✓	✓	✓	✓
	Primary supporting members	✓	✓	✓	✓	✓	✓
Assesments Supported	Minimum thickness	✓	✓		✓		✓
	Section properties	✓	✓	✓	✓		✓
	Presciptive ..	✓	✓	✓	✓		✓
	Ultimate stregth	✓	✓	✓	✓		✓
	Sloshing	✓	✓	✓	✓	✓	✓
	Bottom slamming	✓	✓	✓	✓	✓	✓
Input Mode	2D or 3D based	2D	2D	2D	2D	Both	Both
	Manual modeling	✓	✓	✓	✓	✓	✓
	Import from CAD	NAPA Steel	✓(semi-auto)		✓	NAPA/CAD	✓
	Export to CAD		NA				✓
	Inter Face	✓	✓		DXF		XML
	CSRH loading	✓	✓	✓	✓	✓	✓
Report Generation	Auto report generation	✓	✓	✓	✓	✓	✓
	MS EXCEL	✓				✓	✓
	MS WORD / PDF	✓	✓	✓	✓		✓

All H-CSR software tools provide the users with manuals that may be read thorough when use H-CSR software. Different format are used, such as standalone documents (e.g. BV, CCS, ClassNK) or online interactive manual (e.g. DNV-GL).

When creating a model for the structural scantling of a ship, the user should input the main characteristics of the ship, such as ship dimensions, compartment dimensions and positioning, frame intervals, location of water tight bulkheads, draft at several loading conditions, still water bending moment etc. Figure 26 shows a snap shot of data input to longitudinal strength members.

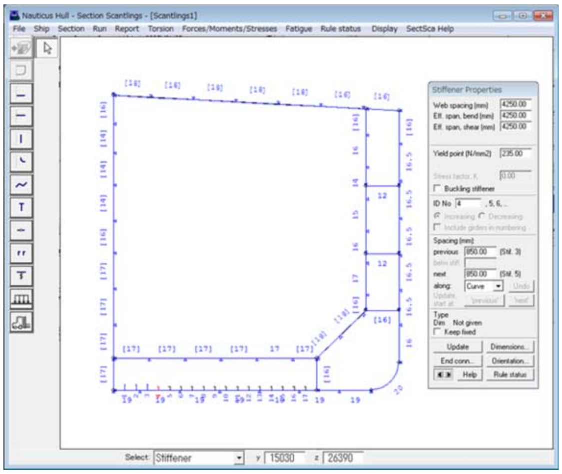

Figure 26: Inputting longitudinal strength members on H-CSR Software tool

Hereinafter, we introduce the modelling procedure to be followed in the very early stage of H-CSR prescriptive rule. First, the software makes hold compartments based on user input dimensions and compartment data. The designer input the main supporting members, arrangement and scantling of longitudinal strength members, typical transverse web section, detail shape of transverse web attached to longitudinal etc. Beside this, corrosion reductions are automatically calculated with user input compartment and tank data. Once the user has defined the main input data for the ship, the H-CSR loads are generated. At this point, the section modulus and the other relevant geometric characteristics of the midship sections can be calculated. In order to simplify and speed up this initial phase, some software tools provide the designers with wizards and/or parametric input methods.

A user friendly graphical user interface simplifies the assessment of the results. The results showed by the software tool highlight each member which needs to be modified after calculation because it doesn't satisfy the rules requirements. Reports are automatically generated by the software and WORD and/or EXCEL format file are obtained. Usually EXCEL format files have detailed information such as each calculation steps, dominant load, corrosion values adopted to members etc.

Information shown in Tables 11 and 12 were obtained from each of classification societies by October 2017 and some functions of prescriptive rule calculation in Table 11 were confirmed in this report.

As stated before, the H-CSR Rules gave extinguish number of FE load cases, and FEA function to support design is one key of the packages. Some packages work with commercial FEA software such as FEMAP, HyperWorks, MSC-Patran and MSC-Nastran and Siemens NX. DSA supporting functions are available in the packages. The functions of auto-meshing and auto-buckling panel should be assessed in detail, because the size and shape of finite elements is very important for the structural analysis (Shibasaki, 2016).

Table 12: Application and function matrix of classification software for H-CSR - DSA

Direct Strength Analysis Software		BV	CCS	CSRS (ABS/LR)	DNVGL	KR	ClassNK
		VeriSTAR Hull	COMPASS CSR-SDP	CSR FE Analysis	Nauticus Hull+GeniE	SeaTrust -HullScan	PrimeShip-HULL (HCSR)/DSA
Base FEA software	Pre and Post processing	FEMAP	Patran	Patran	GeniE	SeaTrust -HullScan	HyperWorks Patran
	Solver	NX/MSC Nastran	MSC Nastran	NX/MSC Nastran	Sestra	MSC Nastran	Nastran / OptiStruct
Componets covered	One lump analysis (every hold at once)						✓
	Global strength (3 hold)	✓	✓	✓	✓	✓	✓
Assesments Supported	Yield check (global model)	✓	✓	✓	✓	✓	✓
	Buckling check (global)	✓	✓	✓	✓	✓	✓
	Structual Optimization*	✓	✓				✓
	Auto screening (fine mesh)	✓	✓	user input and program calculation	✓	✓	✓
	Yield check (fine mesh)	✓	✓	✓	✓	✓	✓
	Auto screening (very fine)	✓	✓	user input and program calculation		✓	✓
	Fatigue life calculation	✓	✓	✓	✓	✓	✓
	Bottom slamming Impact(quasi-static analysis)		✓	Rule calculator + FEA	Rule calculator + 3D-Beam		✓
Input Mode	Import from CAD	✓			✓	✓	✓
	Import compartment	✓ (NAPA Steel)	✓ (NAPA)	✓			✓ (NAPA)
	Corrosion deduction	✓	✓	✓	✓	✓	✓
	Auto meshing coarse		✓		✓	✓	✓
	Auto meshing fine	✓	semi-auto		✓	✓	✓
	Detail shape database (fine)		✓			✓	✓
	Auto meshing very fine	✓	semi-auto		✓	✓	✓
	Detail shape database (very fine)		✓	✓		✓	✓
	Auto buckling panel	✓	✓	✓	✓	✓	✓
	CSRH boundary condition	✓	✓	✓	✓	✓	✓
Report	Auto report generation	✓	✓	✓	✓	✓	✓
	MS EXCEL	✓		✓	✓		✓
	MS WORD	✓	✓	✓	✓	✓	

Once the analysis is completed, auto screening functions are able to identify highly stressed areas in the fine mesh and very fine mesh models. Yield and fatigue life are evaluated according to the H-CSR. Moreover, the tools are equipped with an automatic Report generator which is available on each package for WORD and/or EXCEL format. The relevant input data of the analyzed ship structures, and the outcomes from the analysis are organized and reported in the output document.

Because of the time consuming analysis required to perform the structural design according to H-CSR, CS have developed and are developing flexible functions which are expected to save man-hours in the overall structural design process. SeaTrust-HullScan, which is the structural design assessment software of KR, can automatically generate 2D cross section models for H-CSR Prescriptive calculations and FE models for H-CSR DSA, using 3D CAD models. If a 3D CAD model is not provided, it can generate FE models by connecting two or more cross sections previously modelled in the software for the prescriptive calculation. In the case that a 3D CAD model is provided, it can import the 3D CAD geometry by IGES and hierarchical model data by XML or THS, 2D cross sections can be generated by intersecting with YZ plane, and FE models can be generated surface meshing with the constraint of stiffener. The properties of plate and stiffener can be inherited automatically. Auto-modeling for fine mesh and very fine mesh (t by t) with properties inherited from coarse meshes based on parametric method is also provided in SeaTrust-HullScan software. These functionalities provided by SeaTrust-HullScan will enhance productivities in generating both FE model and Cross section model for H-CSR software (Myeong-jo Son, 2016)

In Shiptec China 2016 (2016), it was reported that CCS is developing a new generation H-CSR software tool, called Compass3D. This software package integrates rapid 3D CAD modeling of ship structures, auto FE modeling, ship stability calculation, H-CSR prescriptive rule calculation and DSA. The CAD/FEM system is developed on the top of Siemens NX platform. 3D ship structure model could be rapidly built by merely inputting key parameters. Any interested cross section and idealization model specified by H-CSR can be generated automatically from the 3D CAD model and be used for prescriptive rule calculation directly. A function of transforming CAD model into FE model which satisfies the requirements of H-CSR is also be provided. It can handle plate seam, bracket toe, hole and stiffener end connection, such as stiffener of transverse web connected longitudinals. It can automatically generate the material, plate thickness, and stiffener profiles, and can automatically import the relationship between structures and compartment, which will be defined in H-CSR DSA.

6.3.2 Aframax tanker modelling for prescriptive rule calculation

The data related to principal dimensions and midship sections of the ship used in this benchmark study were provided by DNV-GL. Figure 27 shows the midship section of this ship. Thanks to the data, the committee members generated structural models by means of CS tools and calculated midship section modulus and ultimate strength capacity of the subject ship. These calculation steps are performed at the beginning of the design stage, and a huge amount of calculations, such as local scantling calculation, direct stress analyses with finite element model, fatigue strength calculations with very fine mesh finite elements etc., normally follow this initial steps in order to have the design project approved by the CS. BV, CCS, CSRS(ABS/LR), DNV-GL and ClassNK provided H-CSR prescriptive rule calculation software tool in order to perform this study.

Starting from the data provided by DNV-GL, the committee members created the midship section of this tanker using the different CS tools provided by the aforementioned CS. It is worth pointing out that the committee members didn't attended any course or received any specific training in order to use these software tools. Nevertheless, the user-friendliness of the tools interface, the well-organized manuals of the software tools, and the support of the CS allowed the members to obtain the results presented in Table 13. It is advised that well experienced designers, surveyor, expert software developers in CS may obtain different results.

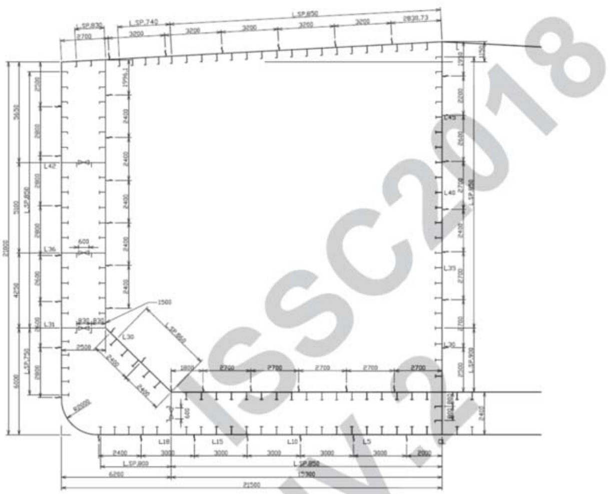

Figure 27: Midship section of template aframax tanker drawn by the committee members

Table 13: Comparison of first output from H-CSR software

Software Name	Template Ship	Mars2000	COMPASS-SDP	Prescriptive Analysis		NAUTICUS	PrimeShip Hull	MAX	MIN	MAX-MIN
Classification Society	(Template)	BV	CCS	ABS LR (*)	ABS LR (*)	DNVGL	NK			
Section Modulus										
Cross Sectional Area, Total	1.00	1.00	1.01	0.99	1.00	1.00	1.00	1.01	0.99	0.02
Actual Hull Iy	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.99	0.01
Neutral Axis	1.00	1.00	1.00	1.01	1.01	1.00	1.00	1.01	1.00	0.01
Actual Hull Iy/z at Bottom	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	0.99	0.02
Actual Hull Iy/z at Deck	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00
Ultimate Bending Capacity										
Hogging (Mu)	1.00	1.00	1.00	0.99	1.01	1.00	1.02	1.02	0.99	0.03
Sagging (Mu)	1.00	1.00	0.99	1.01	1.02	1.00	1.02	1.02	0.99	0.03

*: Data input and calculation were carried out by separate two parties

Hereinafter, the results obtained by the committee members are summarized and discussed. Even if a detailed cross-checking of the input data should be performed to verify in detail their accuracy, cross checking the outcomes of the analysis, reported in Table 13, we notice that there are very little differences among the CS software tools. For instance, the difference in section modulus ranges between -1.5% and 1%. Nevertheless, this small difference may affect the results obtained in the following steps of the structural analysis and we recognize that it may not be satisfactory for structural designers, shipyards and surveyors. Indeed, the reproduction of calculation is not guaranteed if the ship's data are re-input to perform the structural assessment, or an existing ship needs to be classified under a different CS.

Moreover, the compliance of the structural assessment to the H-CSR is based on the outcomes of the calculations performed with these tools. Different input data can lead to different final structural scantling of the ship under design. We think that the difference in the obtained outcomes may be arisen from uncertainty of data input, such as detailed location of longitudinal, start end point of knuckle or curve of outer end of inner bottom plate etc. Some software packages support user friendly input and semi-automatically definition of the coordinates of the longitudinals, but these supporting functions made it difficult to adjust input data and brought small differences between the software. We found different input methods of size for T profiles or longitudinal stiffeners, face plate thickness is neglected in the T profile web height or included. For cut-out modeling on section modulus calculation, in some software tool environments, the user is able to directly model cut-outs while other software packages need one plate to divide the strakes. Specific know-how for each software is necessary and this may reduce the willingness of the users in the tool selection or change. From the trying out the software packages and the result comparison, and a common user interface of input data should be suggested for all designers belonging to shipyards, and know-how of using and input software shall be shared among all users.

The calculation method of hull girder ultimate capacity is described in Part 1 Chapter 5 Appendix 2 Hull Girder Ultimate Capacity of the H-CSR Rules. Because input data was longitudinal members on midship section and not 3D FE model, incremental-iterative method was carried out as described in the Rules. The section areas calculated using each software tool varied within 1% (see Table 13), but the results of ultimate bending capacities varied up to 2%. The differences in the outcomes might be generated by the detailed calculations included in the software, such as step calculation division, peak findings and so on. And detailed programming technics are not shown in the H-CSR. Therefore, as H-CSR software providers, CS are suggested to open the methodologies implemented in the tools and cross check these among the different CS.

Even if these calculations are performed in the first steps of the structural design, main dimensions, characteristics, compartment data, and all longitudinal members are required to be input. Once these data have been input, loads and local strength calculations are simultaneously calculate based on the H-CSR Rules. Then, three-dimensional models are created in the software environment and direct strength analysis can be performed in the following steps. This means that the committee members input almost all data for local strength calculation by themselves and found that there are still small differences on the outcomes from the black-box. From the experience acquired in this study, opening detailed calculation procedures implemented in the software packages and not shown in the H-CSR booklet will be very helpful for all designers and surveyors. A thorough discussion and enhancement of calculation procedures on an open platform for all structural designers will bring superior design bases on the H-CSR.

6.4 Industry point of view

Due to the implementation of H-CSR, the shipbuilding industry faces new challenges requiring higher demand on resources and standards in order to design ships that comply with the new rules. This can lead to the increase of hull structure weight. Rather than increasing the man-hours at the construction site, the extent of coverage in structural analysis at the designing stage has mostly increased. Furthermore, the come-into-force of the new rules has dramatically increased the overall amount of structural details which need to be assessed. Consequently, the amount of structural analysis that should be made at the designing stage has significantly increased, and this has extended the design process. As a result, it has been more difficult than before to supply new ships to the ship owners in a timely manner. With regards to the increased design cost due to the increased designing work, it may be unavoidable that part of this cost growth is reflected in ship price, generating new problems for the industry as a whole.

The purpose of the H-CSR software tools provided by Classification Societies is on one hand to check the conformity of the shipyard's design results with the H-CSR. On the other hand, Classification Societies should recognize that it is also a tool for shipyards and designing companies for designing H-CSR compliant ships. Therefore, the software should satisfy the following conditions (Shibasaki, 2016):

- Ease of inputting design information, visibility of the information, and ease of modification of inputs;
- In respect of structural analysis, full functions for creating the analysis models satisfying the rule requirement;
- Calculation time without causing tediousness;
- In respect of output, ease of visual checking of results;
- Particularly for the display of the dominant loading case;
- Display functions for deformation plots and principal stress;
- Comprehensible reporting capabilities.

This report shows the first stage of the use of H-CSR software. Six different committee members input dimensions and local scantling data, created a 2-D structural model for longitudinal strength calculation and compared the outcomes of the simulations. Each H-CSR software tool offered by the Classification Societies has different input methodologies, different operational ways and different output formats. This implies that there are difficulties to directly compare input data and results from the software tools. This may explain the little discrepancies in the result of this study, discrepancies that have been obtained even if the committee members input the data from the same template of an Aframax tanker design. The H-CSR software with common methodology for data input, modeling, interface and output evaluation might be more expected to decrease slight disharmony of result and furthermore work hours.

Moreover, industries highlight the need of support, not only in checking the compliance to the rules, but also in the optimization of the ship design, in order to mitigate the impact of the rules in particular on new ships weights and costs. Andric et Al. (2016) investigated the possibility of optimization of design introducing as variables not only the scantling but also compartments geometry considering its influence in strength and in loads distribution. Since classification societies software are mainly closed, the proposed approach, based on in-house developed modules, takes few advantages from dedicated tools capabilities. In this scenario, even not considering optimization functionalities directly implemented in classification societies software, a future further development of input – output functionalities, may become an important goal to be pursued.

6.5 Conclusions

Over the last few decades, Classification Societies have provided shipbuilding industry, surveyors, and consultants with software tools, and most of these have had a significant and positive impact on the shipbuilding industry. CSR-OT and CSR-BC were implemented as separate rule sets in April 2006, these rule sets already had many load cases and complex evaluation formulae which required specialized CSR software. In January 2015, H-CSR brought an enormous amount of load cases and complex formulae for the design of new tankers and bulk carriers. This implies that nowadays there is no way to design these types of ships without specialized H-CSR software tools.

There are some H-CSR software packages already offered by Classification Societies which are used in actual ship design. In this study, the committee members used five different H-CSR software tools, thanks to the cooperation from Classification Societies, and the fundamental function of input structural model and results obtained from several software tools were compared. An Aframax tanker was used as template ship. Six different committee members input these data in the software tools in order to model the midship section of the ship and perform some first analysis according to the H-CSR rules. The results obtained from software were almost same, but differences in the input methodologies and modeling techniques of structural details, viewings, result outputs generated some difficulties in obtaining close numerical results and comparing these outcomes. This might also occur in the actual ship design and the H-CSR has forced huge efforts and challenges for the users, increasing the design time and cost of the new ships. Therefore, an improvement of the software tools with a cooperation of Classification Societies should be expected right away.

Since the assessment criteria stated in the H-CSR are recognized by all the IACS Classification Societies, it is expected that, in the future, they will be extended to a larger range of ship types. Moreover, working on H-CSR tools, Classifications Societies developed interesting functionalities for assessment of prescriptive requirements, data exchange, modeling, meshing, load case management and results analysis whose applicability may be already easily adapted on other kind of vessels.

The almost parallel developments of harmonized rules and software tools for their application has to be considered as a good example of integrations between research, regulations and practice. The advantages are not only for the final users, designers and surveyors, but also for the rulers who, thanks to well-timed feedback, expect to bring a stronger rationally based rules sets evaluating also the effects of requirements on the design with their continuous efforts.

7. LIFECYCLE DATA MANAGEMENT

Current trends in the maritime industry, in particular increasing digitalization and automation, mean that there is a need to take a more holistic approach to include the entire lifecycle of a vessel, embracing shipbuilding and shipping. The industry is increasingly demanding more environmentally friendly solutions, combined with greater efficiency and easier diagnostics and maintenance of equipment and systems. Data exchange and the availability of data both onboard ships and ashore will be of increasing importance.

Lifecycle management is key from design to the end of a ship's operating life and becomes an increasingly important issue in industry due to various reasons. Operating costs determine a big part in the financing of a ship and thus need to be minimized as far as practicable. On the other hand, from an environmental point of view, the use of resources during production of the ship and of the production for the fuels required during operation is becoming key interest as soon as alternative fuels (other than conventional liquid fossil fuels) are used. Moreover, data integration from early design to dismantling of the ship is expected to save time and costs in the future. A second big issue in Lifecycle management is the data integration from early design to dismantling.

As a result, data integration became more and more a yard specific issue. Finally, there is also a trend towards smart sensors as part of digitalization. This chapter is divided in three sections entitled Tool development, Data interchange and standards and finally Structural and system health monitoring tools.

7.1 Tool development

It has been shown that leading shipyards carry out their own designs with a huge variety of design tools. The integration of such design tools in the design process (including planning and production) is not an easy task and different handicaps must be tackled today. Two main philosophies can be observed: an "all in one provider" for a number of tools integrated in to one big package (e. g. AVEVA Marine, CATIA, SENER Marine) or the use of specialized tools (Best in Class) with higher integration efforts to be covered by shipyard IT-experts. Both philosophies have advantages and drawbacks and each shipyard has to decide on their optimum approach. In contrast, smaller shipyards often outsource the design and/or work with specific design offices.

The scope of integration is a bigger challenge and not realized in many cases. Indeed, many independent challenges (hydrodynamic optimization, intact and damage stability, strength and vibration assessment, hull fairing, etc.) solved by CAE software's in early design stage and requirements for subsequent detailed design and planning purposes as supported by ERP software's do not actually always allow for a fully integrated design process and data handling. However, first steps have been taken by the industry to tackle these challenges.

Wagner, et al. (2015) present a IT solution that might work in the short-run, they give an overview on Enterprise Architecture Management (EAM) and discuss the application of the methodology in the context of shipbuilding (Product Lifecycle Management) PLM illustrating the advantages but also the main challenges. EAM shows a large potential based on the integrated management of the different architectural layers and helps to manage the change. The analysis provides the best support for the business processes but also to react to customer initiated changes to these processes.

Similarly, Thakker, et al. (2015) illustrate the implementation of 'One Portal' as a single source for all information that is relevant for an employee working in a shipbuilding organization. It should facilitate an employee entering or working in an organization to exactly navigate or search for their processes and go through the work instructions and training material relevant to their process tasks. Such information, which is spread across different applications is becoming available within few steps (or clicks). This work announces a potential increase of 18% in efficiency of finding the information.

Roth (2016) presented a sub-project of Siemens PLM Software to support shop floor workers with a tool that provides the backflow of information into the PLM system in an open and lightweight way. The demonstrator aims at the individual manufacturing industry, such as shipbuilding. One of the prerequisites was to enable partners to update their heterogeneous software systems with as-built shop floor information. Also, a benchmark of different ways to assess the possible methods was demanded. The concept of the software is presented as well as the valuation model for the comparison of PLM-supported process landscapes - especially regarding the data formats being used and the reduction of iteration cycles between shop floor level and construction department. Production Planning and the simulation of production processes are well under way in the maritime industry. However, a serious gap can be identified between those data needed for simulation and those provided by the various design tools. The industry is currently not able to provide a proper flow of information without such gaps in the processes.

Addressing this issue, a potential solution has been presented by Bruun Ludvigsen et al. (2016). This paper proposes a digital twin simulation platform, "Nauticus Twinity", with the vision of providing a more efficient verification scheme for the maritime industry. A digital twin of a vessel consists of a number of simulation models that are continuously updated to mirror its real-life twin. Combining existing technology through implementation of Functional Mock-up Interface (FMI) enables a platform for collaborative simulation and integration of complex systems. A key feature of the simulation platform is the open architecture allowing integration and co-simulation of models developed by DNV-GL and partners. The developed platform facilitates new tools for design, classification, verification, commissioning, condition monitoring, and decision-making throughout a vessel's life cycle. This development focuses on co-simulation and use of digital twins for the new build phase and includes an example of how Nauticus Twinity can improve the commissioning and the verification process for complex integrated systems.

Life cycle management can be approached from three different perspectives: Financial, environmental and customer care including data handling during operation. For decision-making purposes, CAPEX (capital expenditure) as well as OPEX (operational expenditure) must be considered during the design phase of a new vessel. Increasing attention on operating costs has led the builders of complex ship types to assess the operating costs in early design stage (beside typical challenge of offering best price in just designing and building the vessel).

From an environmental point of view, reduction of energy and related GHG-emissions is on the top of the agenda. Other emissions like SOX, NOX are under discussion since many years through the introduction of Emission Controlled Areas. The release of particular matter is getting in focus in ports. For an assessment of the environmental impact, existing methodologies need to be adapted for needs of the maritime industry. Simulation tools for life cycle performance are partly used in large yards and with a focus on structural performance. Systematic life cycle performance assessment is carried out only by leading yards for individual components as well.

Cepeda, et. al (2017) presented a tool development to improve the operating life of a ship' fleet through the use of slow steaming strategies to reduce the operational cost and the emissions. The study proposes a simulation model considering historical data of a bulk carrier's fleet composed by 13 ships from a unique ship owner where the actual navigation condition is compared with a slow steaming and an ultra-slow steaming strategy of navigation. This model considers the speed, fuel consumption cargo transported, and particularly the CO_2 and SO_X emissions. The paper shows that SS has reduced emissions by around 22% over 1 year fulfilling the target of IMO, and savings in operational costs, considering fuel consumption and emissions (CO_2 and SO_X). The use of this tool can help to simulate scenarios with historical data, assisting ship owners in making decisions about the number of ships in their fleet and establishing best operating strategies.

European projects like InterSHIP, BESST, JOULES and THROUGHLIFE have led to significant improvements in larger industry, however smaller companies are lagging behind. There has been encouragement in the industry to integrate the "Life Cylce Analysis in 7 days" along with the "Design in 7 days", so that a complete analytical overview of the ship would be obtained even during the design phase of the ship. However, integration of design tools based on a life cycle management approach is not available yet. Challenges arising from the introduction of new maritime products and small series (complex prototypes) are to be overcome by the industry. Design Tool Integration has been on the agenda continuously, whereas additional life cycle thinking has attracted interest more recently.

7.2 Data interchange and standards

The capabilities of a Ship Design (SD) or CAD (Computer Aided Design) system to import and export data from or to other systems, is nowadays a decisive factor for the penetration and success of such tools in a highly competitive software market. The design of a ship may include several gigabytes of data regarding the ship geometry, structures, equipment, hydrostatics, hydrodynamics and maneuverability, which is processed and represented by different SD or CAD systems, with different data input/output formats, protocols and standards. Despite the differences between systems, the need to communicate between them, has motivated an intensive research on ship data interchange and standards in general, and particularly on ship structural data. The current section describes the latest research on this topic during the last three years.

Lukas, et al. (2015) discuss the potential of 3D data in the ship lifecycle. They study the use of 3D data in various phases of the ship lifecycle, by compiling information among 17 shipyards and maritime suppliers in Germany. The following interesting results are highlighted:

- During the design phase, the 17 companies use 18 different 3D tools with possible different data format.
- AutoCAD™ is still the most used CAD application among these companies
- 75% of the participating companies see an increasing demand for exchanging 3D data between different systems, internally or with external partners

These results highlight the importance of 3D data exchange between CAD systems, and the authors of the study give special importance to open formats and interfaces. The open formats, IGES, STEP, VRML97, X3D, JT and 3DPDF, currently available in the market, were compared using twenty performance criteria. The results have shown that if only a visual representation is necessary, VRML and X3D can be recommended as well as JT. If additional product data such as Product Manufacturing Information is necessary, JT is the clear winner of the benchmark. The success of the X3D format resides on its web version, the X3DOM, which allows visualizing X3D models in common web browsers without any plugin. However, for the case of the JT format, domain-specific specifications are still required.

One of the subjects considered very important for the data exchange between systems, is the simplification of the data to an adequate level of detail depending on the purpose of its use. (Kwon, et al., 2015) present and discuss in detail the simplification of feature-based 3D CAD assembly data of ship and offshore equipment. They also highlight the importance of 3D CAD systems in the process of design, production and delivery in shipbuilding industry. Shipyards and equipment suppliers have different needs with regards to the complexity of 3D CAD data. In general, equipment suppliers create 3D CAD data with a high level of detail (LOD) in order to manufacture the equipment.

On the other hand, shipyards focus mainly in installing the equipment provided by the suppliers, and therefore need to make simplified 3D CAD data to reduce the amount of data to be stored and manipulated in large 3D CAD models. In the study, the authors propose a new evaluation metrics considering geometric and non-geometric information, such as feature volume, ports and outer-boundaries (the modelling requirements of the shipyards), and the characteristics of assembly data. They implemented a simplification system based on the evaluation metrics, and the data to be stored was reduced to at least 25% of the original 3D CAD assembly data, while ports, outer boundaries, and connectivity between CAD parts were maintained. Although the results were good, the authors recognize that there is still work to be done on the evaluation of the quality of the simplified model and on the different connectivity types that are considered in assembly models.

One of the most popular data format in Maritime Industry is the ISO 10303 (STEP) – AP218 product data exchange files. In this case, the standard defines an agreed-upon syntax and structure of 3D modelling constructs and annotations for tolerances and dimensions so that all participants in the manufacturing supply chain can understand each other's models. The STEP AP specifies its information model in EXPRESS modelling language, defining entity-attribute relationships. Lipman and Lubell (2015) discuss the conformance of software applications to the STEP standard, which presents two main challenges: (1) the gap between product design concepts, as presented to software developers, and the concepts in the data model defined in the standard; (2) the correct implementation of the semantics as defined in the standard into the software application.

In order to overcome these challenges, the use of the PMI (Product Manufacturing Information), whose representation is specified in ISO 10303 Standard, is recommended. The PMI consists of a set of annotations and attributes, such as geometric dimensioning and tolerancing, surface texture specifications, finish requirements, process notes, material specifications, and welding symbols, associated with CAD model edges and faces in order to define product geometry and specifications. Lipman and Lubell (2015) show that correct implementation of PMI representation and presentation in STEP files will facilitate the automated-downstream consumption of PMI. Currently the PMI is only implemented in AP203 and AP214, but it is expected and desirable to be expanded to AP218 in a near future.

In the last three years, research of data exchange and standardization as focused also on database systems for data management and visualization. The AVEVA's Asset Visualization is one of such tools, described by Thomson and Gordon (2016), which provides a view of the entire digital asset from the 'as design' to the 'as-operated' phases throughout the life cycle of the ship. The philosophy behind the system is that asset visualization is more than the realistic representation of physical objects. It must concern also the visualization of abstract data associated with the engineering asset. With this in mind, the system captures all data and documents regardless of their source format or authoring systems, classifying and organizing them according to business processes that will consume it. This is achieved by the so called AVEVA NET Gateways, which provide interfaces to these information sources, validate data against defined project data standards and produce web-viewable renditions of documents and drawings.

Another tool developed by the SHIPDEXTM Protocol Maintenance Group, is the Shipdex Viewer. The SHIPDEXTM, described by (Vatteroni, 2016), is an electronic and standardized data format based on XML schemas. It results from a customization for shipping community of the S1000D international specification for the production of technical publications. The SHIPDEX stores ship data in modular units produced in XML format, according to specific XML schemas that are provided together with the specification. It supports links to external documents with illustrations, drawings, multimedia objects in different formats, and it is composed by the following "information sets" regarding the ship lifecycle: (1) Description and operation; (2) Maintenance procedures; (3) Troubleshooting; (4) Illustrated parts data (IPD); (5) Service bulletin; and (6) Maintenance planning. All the data is stored and managed by the so called Common Source Database (CSDB), which is accessed by a proprietary developed user-interface.

A slightly different approach is presented by Morais et al. (2016). They claim that the issue of the data exchange between systems, depends on the ease with which programs can be integrated. The way a software is designed plays a key role in determining that ease of integration as well as future flexibility, and the use of an underlying open architecture is the only way to achieve this goal. This requires an open architecture base platform over which dedicated software is developed. An example of this is given by the Autodesk/SSI shipbuilding software solution which builds on top of the SQL and AutoCAD platforms, on top of which sits SSI's ShipConstructor Marine Information Model (MIM) plus other tools, on top of which sits ShipConstructor and other applications, on top of which sit other applications connected via what SSI calls the SSI Enterprise-Platform.

7.3 Structural and system health monitoring tools

The process of implementing systems able to detect damages on engineering infrastructure is referring to structural health monitoring (SHM). A damage is defined as changes of the material and/or its geometric properties. Several novel methodologies and SHM technologies has been developed recently and latest research on this topic are presented below. Both, cost reduction and prolongation of life cycle of structure are the two main objectives focused by this technology.

An overview of lifecycle management processes for machinery and equipment is provided in Koch, et al. (2015). In this paper, a methodology for building a full ship risk model and decision support system is suggested. Specifically, the collection and storage of measurements such as pressure, flow, temperature, combustion performance, and vibration are elaborated. These are combined with data obtained from robotic platforms and voyage recordings. Accordingly, an innovative data management system for ship machinery using a catalogue data model has been suggested by Taheri, et al. (2015). There, different types of databases are compared, with similarities and differences explained. A ship case study where raw measurements are stored in a suitable database are included. There, inputs from multiple sources are stored and combined before being fed to data analysis tools. Through the presented case study, graph type databases proved to be the most effective choice for marine condition monitoring applications, using both static and dynamic input sources.

The study by Ravina, (2017) analyses a concept design of an autonomous mechatronic unit for inspection of holds, is oriented to inspection of the interior walls of vessels, in particular tanks and holds, difficult or dangerous to reach and requiring a large number of measurements. A concept design of a self-moving unit for inspection of holds and tanks of cargo ships is proposed: feasibility and applicability are shown in this study. This system is not designed for a complete replacement of skilled technicians, but as support of inspections in spaces dangerous or difficult to reach. The study is based on tanker ships, however in many ship type is fundamental to perform periodic inspections to monitor the thickness of the hull, of welding and of metallic walls in general. The different design phases are described in the paper, showing the feasibility of the proposal. The structural parts of the unit are analyzed designing two different geometries, and the support plate is analyzed from the structural point of view with finite elements techniques: it is composed of two parts which are mutually connected in the assembling phase of the robot.

Decò, et al. (2015) develop a risk-informed approach for ship structures that integrates structural health monitoring (SHM) information. Through an application, real-time optimal short-range routing of ships is presented. Decò, et al. (2015) present an approach for the integration of SHM data, through Bayesian updating, into risk real-time assessment of ship hulls. A novel closed-form solution for short term statistics based on Raleigh prior distribution is developed and compared with a simulation-based technique. Then, an approach for real-time optimal routing of ships has been presented. Two-and three-objective optimization problems are solved by minimizing the estimated time of arrival (ETA), total risk, and fuel costs. The results are shown in the form of Pareto-optimal sets. Mission profiles including total risk, reliability index, fuel cost, ship path, ship speed, and cumulative time from departure are obtained for a Joint High-Speed Sea lift. The information obtained from SHM and different sea weather maps are integrated with in the developed optimization framework.

Other studies use finite element method with improvement algorithms to evaluate specific structural elements. An algorithm named as inverse Finite Element Method (iFEM) was developed at NASA Langley Research Centre and used by Kefal et al. to evaluate specifics elements, ships and systems in some of their works. The first study in this area is about the perform displacement and stress monitoring of a typical chemical tanker mid-ship based on iFEM methodology (Kefal, et al., 2016). The iFEM formulation is based upon the minimization of weighted-leastsquares functional and requires discrete strain data obtained from on-board sensors in order to reconstruct the displacement, strain, and stress fields. In-house hydrodynamic and finite element software are utilized for simulating the on-board strain-sensor data in order to represent a floating structure in real sea environment. The results obtained from FEM analysis is utilized as a source to simulate in-situ strain data used in iFEM analysis as input. Finally, iFEM and FEM displacements are compared and the effects of locations and number of sensors on iFEM solution accuracy are discussed. This iFEM algorithm is a very promising system for health monitoring, performing a precise shape- and stress-sensing of marine structures.

An additional (Kefal, et al., 2016) study of displacement and stress monitoring of a Panamax containership is performed based on the iFEM methodology. Several direct FEM analyses of the parallel mid-body are performed using the hydrodynamic wave bending and torsion moments. Then, experimentally measured strains are simulated by strains obtained from high-fidelity finite element solutions. (Kefal, et al., 2016) present three different iFEM case studies of the parallel mid-body are performed utilizing the simulated sensor strains, pure vertical bending case, pure horizontal bending case and pure torsion case. Then, the deformed shape and von Mises stresses of the containership are reconstructed using in-situ strain data obtained from each proposed network of strain-sensors. According to the accuracy of the displacement and stress results, the optimum strain-sensor locations are identified and clearly demonstrated for each iFEM case study. Finally, the numerical results confirmed the robustness of the iFEM methodology for monitoring multi-axial deformations and stresses of a Panamax containership floating in beam sea waves.

The use of finite element methods is deepened by other authors and combined with other methods to get better results. The use of finite element methods is deepened by other authors and combined with other methods to get better results. Yan et al. (2015) combine the Bayesian framework with extended finite element method (XFEM) to provide a statistical approach for nondestructive multi-flaw identification considering uncertainties from modeling errors and measurement noise. Specially, a trans-dimensional reversible jump Markov chain Monte Carlo (RJMCMC) method is employed to draw the posterior distributions of the flaw parameters due to the missing knowledge of the number of flaws. This analysis is in order to monitor structures to detect flaws at an early stage to prevent catastrophic failure.

The Bayesian methods are also used to estimate the fatigue damage present in offshore platforms by Green, et al. (2016). This first involves running a series of Finite Element simulations, thus establishing how the modal characteristics of an offshore structure model vary as a function of its material properties. Data based modelling techniques are then used to emulate the Finite Element model, as well as estimates of model error. The uncertainties associated with estimating the hyper parameters of the data-based modelling techniques are then analyzed utilizing Markov chain Monte Carlo (MCMC) methods. The resulting analysis takes account of the uncertainties which arise from measurement noise, model error, model emulation and parameter estimation. The use of use finite element methods in oil and gas industry is also present as structural and system health monitoring tools. The study of Kefal et al. (2017) investigates the applicability of iFEM, for displacement and stress monitoring of offshore structures for the first time in the literature. Displacement and stress solutions obtained from iFEM analysis are compared to those of reference solutions.

Shen et al. (2015) propose a new damage assessment method for aging offshore platforms based on dynamic tests, it provides information on whether damages occurred between the times of two adjacent measurements. A numerical offshore platform will be used to demonstrate the proposed method, including noisy modal parameters, low damage severity, and spatial incompleteness. The model uses one theoretical improvement is that the requirement for using the stiffness matrix of the finite element model (FEM) to replace the one of the measured models can be ignored in the calculation of the modal strain energy (MSE) of the measured model. The other improvement is that the influences of the damages accumulated before the first measurement on the damage detection that occurs between the two measurements can be reduced greatly. The numerical studies also demonstrate that the proposed method can localize the damages that occur between the times of two adjacent measurements and evaluate these damages properly, even in spatially incomplete situations.

Moreover, in the oil and gas industry the fatigue-life prediction of offshore pipelines becomes a major issue to ensure the integrity and reliability of offshore pipelines since many catastrophic failures of piping components were caused by fatigue crack growth. Fatigue crack growth of pipelines has been studied extensively by experimental tests. It is well recognized that scale factors and the large amount of costs on the experimental set up are major challenges to conduct a full-scale fatigue test. The adequate confidence to design offshore oil and gas system productions should be built upon a series of preliminary fatigue tests using full-scale numerical simulations. Zhang et al. (2016) make a systematic investigation about the fracture resistance behavior of offshore pipelines containing an elliptical embedded crack under cyclic tension loadings. Extended finite element method (XFEM) is adopted for numerical simulations. The influences of different initial crack length and stress ratio on fatigue crack growth are investigated in detail. In addition, the thorough interpretation and discussion on fatigue response of the flawed pipe lines with the elliptical could be helpful in designing offshore oil and gas system productions.

The structural and system health monitoring tools have not only been designed to prevent failures and to systematize inspections, but in the future for maintaining and increasing oil and gas production. Related to this are studies for exploring the potential for extending the lifetime of offshore platforms by implementation of Structural Monitoring Systems (SMS). The paper by Skafte et al. (2014) use an expansion technique as a first step in the sequence of assessing the actual lifetime of a platform. Mode shapes and natural frequencies are estimated using operational modal analysis. The mode shapes are then expanded by expressing each experimental mode shape as an optimal linear combination of selected modes from a finite element model. The offshore platform of the case study, Valdemar, which is fully instrumented with accelerometers, GPS, strain gauges and wave radars, is chosen as a case study. Results show that the measured response can be expanded with high precision, which provides valuable information when assessing the actual lifetime of the platform. It is also shown that the expansion technique can be used for assessment of measurement uncertainties.

Skafte et al. (2017) study the offshore structures by the continuously dynamic loading from wind and waves to which it is subjected. The monitoring the vibrations of the structure using real time operating data enables an assessment of the general health state of the structure. Skafte et al. (2017) propose a method for full-field strain estimation by combining experimental measurements with a well correlated Finite Element (FE) model. This study presents how the response of an offshore structure can be divided into two parts: The low frequency response from the quasi-static effect of the wave load, and the high frequency response from the dynamic properties of the structure. It is further demonstrated how strain histories below the waterline can be estimated using accelerations measured on the topside of the structure. The low frequency response is expanded using the quasi-static Ritz-vectors, and the high frequency response is expanded using modal decomposition. This work should be seen as a first step towards a general framework for fatigue monitoring of offshore structures. The work shows promising results regarding estimation of the strain history in unknown points.

The INCASS (Inspection Capabilities for Enhanced Ship Safety) EU FP7 project dedicated a work package to the development of a database system product for lifecycle data management. (INCASS, 2014b) report provided an overview of system architecture and general workflow supported by the developed database system, including descriptions of main applications and components. Specific applications focusing on the handling of machinery and equipment were additionally developed. An additional (INCASS, 2014c) project report elaborated on the data exchange capabilities of the developed software along with details on the implementation of the OpenHCM format for the exchange of structural condition monitoring data and the derivation of the respective MCM format for machinery condition monitoring data. Accordingly, (INCASS, 2016a) presented the functions that have been implemented to allow for ship-to-shore data transfer. Finally, in (INCASS, 2016b) the design of the Central Stochastic Database (CSD) is presented, following the description of individual tools provided in previous deliverables. The latter report illustrated the data flow between other INCASS tools and the CSD.

8. OBSTACLES, CHALLENGES AND FUTURE DEVELOPMENTS

The Committee see the following important trends in ship and offshore structural design based on what we have seen in the recent years: (1) IACS Common Structural Rules for Bulk Carriers and Oil Tankers, (2) IMO Energy Efficiency Design Index (EEDI), (3) new design paradigm, (4) accurate optimization models including FEA, (5) analytical methods for impact analysis, (6) complete risk assessment frame-work for ship accident, (7) mega container ship, (8) unmanned ships. These concepcts can also identify areas of future industrial and / or research developments. Based on these trends, we see the challenges and obstacles described in more detail below.

8.1 Common Structural Rules for Bulk Carriers and Oil Tankers

In July 2015 the Harmonised Common Structural Rules for Bulk Carriers and Oil Tankers (CSR BC&OT, HCSR) suggested by the International Association of Classification Societies (IACS) entered into force (IACS 2014). The HCSR replaced the separate rules set of the Common Structural Rules for Bulk Carriers (CSR-BC) introduced by IACS (2012a) and the Common Structural Rules for Double Hull Oil Tankers (CSR-OT) IACS (2012b) and harmonized the two rule sets into one. Furthermore, the HCSR introduced some new requirements. In the previous rule set initially implemented in April 2006, the rules were developed by separate teams working on either the ones for bulk carriers or the ones for double hull oil tankers. Such an approach necessitated the harmonization of different rule sets, which should be based on the same fundamental structural strength theory and natural phenomena. To be more precise, HCSR are applicable only for double hull oil tankers that have a length of more than 150 meters. For HCSR, though applicable for bulk carriers, it is important to note that these are suggested for bulk carriers exceeding a length of 90 meters and can be either single or double skin. The following ships, though are classified as bulk carriers by designers, need not be designed in compliance to HCSR: Ore-Bulk-Oil Carriers or OBO Carriers, Combination Carriers, Bulk carriers carrying woodchips or similar cargo, Bulk carriers with self-unloading facilities. In the above cases, HCSR compliance is not required, as these are to be designed following the rules of the authorizing Classification Society. All IACS member Classification Societies are required to enforce the HCSR requirements after they are officially in effect on 1 July 2015.

Referring to the challenges that the HSCR application will need to address, Shibasaki (2016) suggested that "Due to the implementation of HCSR, the shipbuilding industry faces new challenges requiring higher demand on resources and in standards in order to comply with the new rules compared to the former CSR, which can lead to the increase of hull structure weight. Rather than increasing the man-hours at the construction site, the extent of coverage in structural analysis at the designing stage mostly increased, and the parts and regions subject to detailed structural analysis have dramatically increased. Consequently, the amount of structural analysis that should be made at the designing stage has significantly increased, which prolonged the design period. As a result, it has been more difficult than before to supply new ships to the ship owners in a timely manner. As for the cost increase due to the increased designing work, it may be unavoidable some of that increase is reflected in ship price, thus becoming a problem for the industry as a whole."

Since the HCSR has focused on oil tankers and bulk carriers, it has allowed for the time and scope to define permissible limits of loading, and formulas to establish the appropriate scantling criteria, depending on all loading patterns that can be considered in bulk carriers and oil tankers of all configurations of tanks and holds. This also includes all possible combinations for alternate hold loading in case of bulk carriers.

Considering the above, HCSR are more demanding that the replaced rule set. The scope of the FEM, ultimate, buckling and fatigue strength analyses required increased considerably resulting in increased ship safety. The analyses are to be directly performed for the whole cargo holds/tanks region of the ship while in the previous two rule sets such analyses was required mainly for the midship region. Moreover, the previous rules only provided for snippets of instructions for modelling the ship hull for finite element analysis. Moreover, HCSR has included detailed instructions of the procedures to be followed to model each part of the hull also following industry standards on checking the adequacy of calculated scantlings by finite element analysis. Modelling and correct meshing of end connections is very important in obtaining correct results, hence the new rules have defined methods and boundary conditions to be maintained while modelling the hull girder and local strengthening structures.

Moreover, the calculation workload necessary under HCSR requirements will be at least threefold in comparison to (former) CSR requirements. HCSR assures comprehensive assessment of the entire ship hull structure. The replacement of CSR by HCSR requirements will no doubt improve bulk carriers and tankers hull safety in terms of structural strength, but also generate immense workload in the design process. Consequence assessments studies performed indicated that CSR requirements are slightly more demanding compared to the previous rule sets while also increasing the scantlings will not be greater than 3%, in general (PRS 2017). In this respect, unifying and harmonizing the technical requirements of the CSR for tankers and bulk carriers, HCSR incorporate new requirements for more comprehensive structural analysis at the design stage, including FEM analyses covering the entire range of cargo hold structures, as well as new formulae for buckling, fatigue, and residual strength criteria to enhance safety and reliability.

HCSR requirements also entail the development of sophisticated IT tools. Classification Societies have developed software platforms for calculating hull strength of bulk carriers and tankers in line with the projected IACS HCSR. Computer programs are used to calculate thickness plating and plating stiffeners cross section, to perform zone strength FEM analysis, calculate fatigue life, and resistance to buckling and hull design load during hull bending. The majority of Classification Societies have started developing own computer systems which will allow to effectively carry out analysis required by HCSR in order to assist ship designers with the design of hull structures. The developed software can be used to prepare technical reports and to verify the compliance of designed vessels with international standards. The methods of finite element model analysis have also been incorporated into the procedures followed by the FEA modules used by Classification Societies. Software packages facilitating efficient generation of FEM meshes, the input of local and global loads to FEM models, "automatic" assessment of resistance to buckling of the hull structure and the calculation of geometric stress for fatigue life are becoming indispensable.

Following the above, HCSR currently receive continuous feedback from industry practical working conditions. The new goal-based HCSR mark the beginning of changes that should improve ship structural safety and the need for designers, Classification Societies, shipyards and the industry to expedite efforts and catch up with scientific progress and public expectations. Classification Societies need to endeavor and be ready to share knowledge and experience with other stakeholders of the maritime market. Following the first version of the HCSR issued in 2015, the HCSR was updated to include a corrigenda and an urgent rule change notice, which were published and became effective on 1st July 2017.

Further to the above, updating of the HCSR is ongoing. Issues to be discussed are related to the interpretation of thickness effects in the simplified fatigue strength calculation, the minimum still water bending moment for yield strength evaluation and the fatigue strength evaluation. Following a private communication with an IACS member (IACS, 2016) "Since the adoption of the Common Structural Rules (CSR), IACS has been committed to transparency and consistency in the implementation and application of the Rules. The IACS CSR Knowledge Centre (KC) was established to facilitate this." The KC had been quite useful across the industry including shipbuilders and Classification Societies, since it allowed for access to common interpretation and feedback from all relevant industry stakeholders. Eventually, the IACS CSR Knowledge Center (the KC) was not available since August 2016 (IACS, 2016):

"*Since the adoption of the Common Structural Rules (CSR), IACS has been committed to transparency and consistency in the implementation and application of the Rules. The IACS CSR Knowledge Centre (KC) was established to facilitate this. After a careful review of the input from the industry, IACS has decided to make the KC an internal database available to IACS members only. This decision was taken to avoid misunderstandings and early application of proposed Rule Changes".*

The industry will be able to raise questions and provide input to any IACS member, and IACS members will document questions and answers to the KC to continue to support uniformity and consistency. Proposed Rule Changes will follow the formal Rule Change Proposal Process. As you are aware, this process provides industry with two opportunities to comment, one directly in response to IACS consultations and the other by way of input to the technical committees of IACS' Member societies."

While at the moment the IACS CSR KC website is not available to non-IACS Members, the new rules apply to all bulk carriers over 90 meters long and all oil tankers over 150 meters long contracted on and after July 1, 2015. In this respect, a future challenge remains with regards to the ship structural design and optimization of the Common Structural Rules for Bulk Carriers and Oil Tankers.

8.2 Energy Efficiency Design Index (EEDI)

The methodology of ship structural design to optimize the Energy Efficiency Design Index (EEDI) was developed since the reduction of CO2 emissions has been the key target since IMO's Marine Environment Protection Committee (MEPC) published its findings in 2009 (IMO 2009a). At the same time, IMO published a report IMO (2009b) containing: (i) present and future emissions from international shipping; (ii) the possibilities for reduction of these emissions through technology and policy; and (iii) impacts on climate from these emissions. A number of measures resulting in technical and operational reductions were made mandatory in 2011. In this respect, IMO working group suggested that all new ships above 400 GT would have to implement the new EEDI in the near future.

The adoption by IMO of mandatory reduction measures for all ships from 2013 onwards will lead to significant emission reductions. Among these and nearly all new built ships have to conform is Energy Efficiency Design Index (EEDI). The international maritime community expect that the EEDI will result in more energy efficient ships, in reduced emissions of Green House Gas (GHG) emissions, in environmental effectiveness and in significant contribution by shipping industry to the global efforts to stem climate change. This provides a method of establishing the minimum efficiency of new ships depending on their type and size. With increasing competition, the key to companies' survival will be to design and operate the ships efficiently. The following year, IMO published a report IMO (2014) which provides an update of the estimated GHG emissions for international shipping in the period 2007 to 2012.

IMO accepted that such an index should reflect only the technical aspects such as the optimization of engines, hull and propeller or the use of non-fossil fuels, and not the operational or commercial aspects. According to IMO (2017), the EEDI formula is not applicable to all ships. Indeed, it is explicitly recognized that it is not suitable for all ship types (particularly those not designed to transport cargo) or for all types of propulsion systems, (e.g. ships with diesel-electric, turbine or hybrid propulsion systems will need additional correction factors). Indeed, the first iteration of the EEDI methodology has been purposefully developed for the largest and most energy-intensive segments of the world merchant fleet and cover the following ship types: oil and gas tankers, bulk carriers, general cargo ships, refrigerated cargo carriers and container ships. For ship types not covered by the current formula, suitable formulae will be developed in due course to address the largest emitters first.

In the current phase designers relied on retrofit solutions in order to achieve slight gains related to ship structural efficiency. In later phases tougher restrictions will be imposed which will necessitate additional changes in the structural design. The potential technologies suggested which may improve the EEDI can be related to: (1) hulls with less resistance and improved steering configurations, (2) more efficient aft-ship, propeller and rudder arrangements, (3) lower energy consumption in main and auxiliary engines, (4) switch from oil to natural gas as main fuel, (5) miscellaneous technologies to reduce minor energy consumers (deck paint, pipe insulation, lighting, air conditioning, etc.), (6) zero or minimum ballast configurations (e.g. by alternative design or ship type), (7) marine fuel cells; and hybrid ships (e.g. wind power, solar panels, and use of light materials, etc.). Following the above suggested options, it would be beneficial to investigate whether the EEDI methodology will influence the ship structural design and related methodologies developed to address such a challenge. That is: ship structural design and optimization for Energy Efficiency Design Index (EEDI).

8.3 The new design paradigm

Today's ship structural design is highly integrated with other design development activities, such as production, costing, quality control, among others. At the same time essential elements of the modern shipbuilding industry are related to environmental concerns, safety, passenger comfort, and life-cycle issues. Within this paradigm shift, the new designs should facilitate the productivity sequence, be cost-effective, incorporate aspects related to safety and environmental considerations while also being functionally efficient. The challenge: provide a new design paradigm that will take into account of the entire life cycle of ship structure.

8.4 Formulation of accurate optimization models including FEA

In order to enable ship global structural optimization in a realistic way, it is still necessary to either use simple tools, like the tools based on prescribed classification society rules, or use a method of problem simplification within the optimization loops in order to reduce the number of degrees of freedom of the original/standard FEM model. The challenge: identify the methods needed to build accurate global structural models in order to solve ship and offshore structural optimization tasks that take into account the FEA; however, without excessive simplification of structural modelling.

8.5 Analytical methods for impact analysis

Several authors have recently developed procedures and tools to evaluate the structural response of ships and offshore structures subject to impacts. These analyses are usually performed using a FE explicit non-linear general purpose software. The high computational cost of these simulations triggered research activities aimed at the development of tools based on analytical methods that allow the estimation of forces and energy developed in ship collisions in a preliminary analysis. Such methods should be able to carry out a fast evaluation of different collision scenarios. This allows the designer to identify the worst collision scenarios and to perform explicit FE nonlinear analysis on the selected case. The challenge: employ analytical methods that allow the estimation of forces and energy developed in ship collisions in a preliminary analysis.

8.6 Development a complete risk assessment frame-work for ship accident

The risk-based design concept has been gradually accepted in recent years. However, it is still at a development stage and its progress is relatively slow. The current research in this subject is mostly focused on the analysis of individual ship or individual accident scenarios. It is necessary to establish a complete risk assessment framework for ship accident scenarios to support risk-based ship design. The challenge: a complete risk assessment framework investigating ship accident scenarios to support risk-based ship design.

8.7 Mega container ship

Mega container ships with cargo capacity in the range of 12,500-22,000TEU provided shipowners with increased earnings due to economies of scale. The latest figures show that the container vessels capacity is set to increase to unprecedented heights (The Maritime Executive, 2017. However, the above expansion is also prone to associated challenges. Among them, structural design and optimization of ever larger container ships is of key importance. De Haas and Burnay (2017) discuss the issues and challenges associated with mega container ships and the actions that can be taken to mitigate the risks associated with designing, building and operating this new class of vessel:

"*The exceptional size of the hull and its inherent flexibility could ultimately prove to be limiting factors for the mega container ship. Issues such as 'springing' or 'whipping' are still to be fully understood and more research and full-scale measurements are required to ensure adequate structural capacity over the ship's lifetime. Relocating the accommodation structure from the stern, to amidships can help reduce the longitudinal bending moments but the naval architect must still resolve related issues such as shaft alignment and manage the deflections that will occur during operation - the larger the ship, the longer the shaft and the greater challenge to ensuring satisfactory shaft alignment. The ultimate hull girder strength could still be limited by the thickness of the steel used as practically, it is very difficult to manufacture mild steel plate much thicker than around 100mm. Areas such as hatch coaming tables, can be very sensitive to excessive forces, especially in bending and hence the natural tendency would be to look at utilizing high tensile steel, but the significant increase in material costs could have a negative impact on the profitability of operating the vessel.*".

According to the OECD International Transport Forum report (OECD/ITF, 2015), efficiency gains from larger ships have been steadily declining – and further increase in maximum container ship size could increase the overall cost of transporting goods. However, with the latest 'mega-ships', economies of scale may have reached their peak. Bigger ships deliver economies of scale at sea, but they also involve greater costs associated with cargo handling, additional investment in ports, and greater concentration of risk. As reported by The Economist (2013) and The Financial Times (2015), global trade growth will be much slower than decades ago. The construction of vessels with cargo capacity of or beyond 25,000 TEUs may be a challenging task in the near future. Research and design work related to the construction of such units may therefore be slowed down or even suspended. The challenge: structural design and optimization of 25,000TEU container vessels. The obstacle: slow down or stop further work in this area (Bonney 2015).

8.8 Unmanned ships

In recent years, a rapid development of technology has been observed related to the emergence of the first unmanned ships or such vessels for which the human intervention during the voyage will be minimal. According to analysts, this may already be the case as soon as 2025. Towards that direction, industry consortia have set a number of key milestones for the development of unmanned ships (Fig. 28): 2020 – reduced number of crews through the introduction of remote support; 2025 – remote-controlled unmanned vessels in offshore shipping, 2030 – remote-controlled unmanned ocean-going vessels; 2035 – Autonomous unmanned ocean vessels (Rolls-

Royce, 2017), explicitly by definition no one is onboard. It is expected that the use of an autonomous vessel would minimize the operating costs of such ships and maximize its capacity (better use of hull shape). Other industry sources suggest that the first autonomous zero emissions ship will be ready for 2010 (Green4Sea, 2017).

Maritime administrations, class societies and designers should already be prepared for the coming challenge. Discussions have been initiated on how today's international rules can be applied to modern technologies and ships that will change the face of shipping. One of the paramount challenges however remains on how to adapt legislation especially related to security issues. It will be necessary, in addition to technological development, to prepare appropriate standards and requirements for maritime safety management. With extensive experience in maritime safety and the knowledge of other areas of the economy, we can prepare for the arrival of a new stage in shipping history. It needs to be investigated whether the existing methods of structural design of manned ships can be used without the substantial changes for autonomous vessels. If not, then it will be necessary to undertake all the necessary work to update and develop such standards. The challenge: ship structural design and optimization for autonomous shipping.

Figure 28: The next steps in autonomous ship development (Rolls-Royce, 2017).

9. CONCLUSIONS

The Committee performed an extensive and thorough analysis of the ships and offshore industry review on design methods over the last three years, which revealed a number of interesting features. In this case, Chapter 2 continues the work on optimization methods, surrogate modelling and variable fidelity approaches. “Design-for-X” (DfX) including Design for life-cycle performance, Design for maintenance & repair and Design for safety remain a strong topic and a summary of the most recent developments related to the design for specific performance aspects has been provided. Following the trends indicated by the work of the previous Committee, DfX is closely related to the current tendency towards goal-based design methodologies in general and risk-based design in more details, also recently endorsed by International Maritime Organization (IMO) regulations.

Related to the most recent updates with regards to the development of the design tools for marine structures, Chapter 3 provides the progress of Computer-Aided Design (CAD) packages for ship design while particular focus is placed on the development of Virtual Reality and Augmented Reality tools and their use in ship design. Additional work performed on new simulation packages for ship structural design and risk-based design software tools is also presented in this Chapter.

Moreover, despite sharing common ground in terms of design methodology principles, the specific particulars of each different offshore structural design together with a strong dependency on previous specific experience, have led to addressing structural design and associated methods separately for different types of offshore structures. These are addressed in Chapter 4 discussing the topics of design methodology used in offshore structures design, the design challenges and trends, the standardization and asset integrity and maintenance, as well as the design and methodology developments. Moreover, a survey on the use and application of design software used for offshore structures modelling was performed covering an area of major interest.

State-of-the-art vs. state-of-practice was a new theme into the ISSC IV.2 committee's work in order initiate the discussion and bridge the gap in between the research work presented within the committee's remit and the practical applications that may stem out of it. Taking into account that "practice" is the actual application or use of an idea, belief, or method, as opposed to theory related to it, the "state-of-practice" definition provided the best design process which will be also integrated with production, maintenance and repair available in everyday engineering systems. Initially examining the areas of most interest within the last four Committees' work, chapter 5 introduced a way to bridge the gap in between research and applications by suggesting the Theory-to-Practice-Ready Papers (TPRP).

In Chapter 6, the examination of various Classifications Societies software continued to take place following the preceding Committee's work. This time the Committee decided to expand its scope to provide a benchmark study comparing the application of the latest version of the Harmonized CSR of various classification societies in the case of a double hull tanker. While there are difficulties to directly compare input data and results from the software tools due to different input methodologies, operational ways and output formats, this may explain the small discrepancies in the result of this study, even if the Committee members used input data from the same template of an Aframax tanker design. Moreover, industry highlight the need of support, not only in checking the compliance to the rules, but also in the optimization of the ship design, in order to mitigate the impact of the rules in particular on new ships weights and costs. Moreover, working on H-CSR tools, Classifications Societies developed interesting functionalities for assessment of prescriptive requirements, data exchange; modeling, meshing, load case management and results analysis whose applicability may be already easily adapted on other kind of vessels.

Chapter 7 presented the latest developments and trends in the lifecycle management of ships including the updates on tool development, data interchange and standards and structural and system health monitoring tools. Current trends in the maritime industry, in particular increasing digitalization and automation, mean that there is a need to take a more holistic approach to include the entire lifecycle of a vessel, embracing shipbuilding and shipping. The industry is increasingly demanding more environmentally friendly solutions, combined with greater efficiency and easier diagnostics and maintenance of equipment and systems. Data exchange and the availability of data both on-board ships and ashore will be of increasing importance. Moreover, data integration from early design to dismantling of the ship is expected to save time and costs in the future. A second big issue in lifecycle management is the data integration from early design to dismantling.

Finally, the last chapter introduced areas, which will be of particular importance and interest in the coming years. This reflects the continuing efforts on common structural rules for bulk carriers and oil tankers, the Energy Efficiency Design Index (EEDI), the unmanned ships and the mega container ship and the formulation of accurate optimization models including FEA. Additional areas of future scope can be the analytical methods for impact analysis, the development a complete risk assessment framework for ship accident and the development of a new design paradigm considering the entire ship production sequence.

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REFERENCES

Acín, M. and Kostson, E. (2015) Tools and Automation Capabilities for Modeling Marine Structures. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 418-432.

Agusta, A., Thöns, S. and Leira, B. J. (2017) Value of Information-Based Inspection Planning for Offshore Structures, in. 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway: ASME, p. V03BT02A035.

Albright Jr, R. A. (2017) Solving the Drone Data Dilemma, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Anderson, J. D. and Pickup, M. (2017) Evolving Business Models, Concepts will drive Offshore Recovery, Offshore Magazine. Available at: http://www.offshore-mag.com/articles/print/volume-77/issue-5/upstream-investment/evolving-business-models-concepts-will-drive-offshore-recovery.html.

Andrade Sthéfano L., Gaspar Henrique M. & Ehlers Sören (2017) Parametric structural analysis for a platform supply vessel at conceptual design phase – a sensitivity study via design of experiments. Ships and Offshore Structures. Vol. 12, N. sup. 1. Pp S209-S220.

Andric, J, Piric, K, Prebeg, P, Andrisic, J, Dmitrasinovic, A. (2017b) Structural design and analysis of large "open type" livestock carrier, ICSOS 2017: Proceedings of the International Conference on Ships and Offshore Structures, Sören Ehlers & Jeom Paik & Young Bai (Eds.), Shenzhen, China, 11-13 September, 2017.

Andric, J., Prebeg, P. and Piric, K., (2017a) Influence of different topological variants on optimized structural scantlings of passenger ships, Progress in the Analysis and Design of Marine Structures, MARSTRUCT 2017, Lisbon.

Andric, J., Pero, P., Piric,P., Kitarovic, S., Zanic, V., Cudina, P., Bezic, A. and Andrisic, J. (2016) FE based structural optimization according to IACS CSR-BC. In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

Andric, J., Prebeg, P., Piric, K., Kitarovic, S., Zanic, V., Cudina, P., Bezic, A. and Andrisic, J. (2016) FE based structural optimization according to IACS CSR-BC, In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

Andric, J., Prebeg, P., Piric, K., Kitarovic, S., Zanic, V., Cudma, P., Bezic, A. and Andrisic, J. (2016) 'FE based structural optimization according to IACS CSR-BC', in PRADS 2016 - Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures.

Antony, A., Park, Y.-C., Zou, J. and Jamnongpipatkul, A. (2015) Gulfstar - Naval Architecture From Design to Hull Installation, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Bai, Y. and Jin, W. (2016) Marine Structural Design. 2nd Ed. Oxford: Butterworth-Heinemann.

Banke, J. (2010, August 20) Technology Readiness Levels Demystified. Retrieved from https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html, accessed on: 01/11/2017

Beckman, J. (2016) Information Management System assists V. Filanovsky Construction Process, Offshore Magazine. Available at: http://www.offshore-mag.com/articles/print/volume-76/issue-12/engineering-construction-installation/information-management-system-assists-v-filanovsky-construction-process.html.

Benyessaad, O., Barras, S. and Rocha, G. (2017a) How Classification Societies can be Efficiently Involved in the Current Offshore Industry Cost Reduction Era, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Benyessaad, O., Barras, S. and Rocha, G. (2017b) How Classification Societies can be Efficiently Involved in the Current Offshore Industry Cost Reduction Era, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Bertram, V. (2017) Future of Shipbuilding and Shipping – A Technology Vision. In: Proceedings of the 16th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'17), Cardiff, pp. 17-30.

Boman, K. (2017) Drilling Deeper into Data, Offshore Engineer. Available at: http://www.oedigital.com/component/k2/item/16287-drilling-deeper-into-data (Accessed: October 3, 2017).

Bonney, J. (2015) Maersk CEO: 25,000-TEU ships possible but not practical, Mar 02, 2015, https://www.joc.com/maritime-news/container-lines/maersk-ceo-25000-teu-ships-possible-not-practical_20150302.html, accessed on 13 November 2017.

Bonnin-Pascual, F. and Ortiz, A. (2014) Corrosion Detection for Automated Visual Inspection. In: ALIOFKHAZRAEI, D. M. (ed.) Developments in Corrosion Protection.

Boutrot, J. and Legregeois, N. (2016) Integrity Management Services for Floating Units from Design to Decommissioning, in Emerging offshore technology and deepwater trends: 21st Offshore Symposium 2016: Houston, Texas, USA, 16 February 2016. Red Hook, NY: SNAME/Curran Associates, Inc.

Boutrot, J., Giorgiutti, Y., Rezende, F. and Barras, S. (2017a) Reliable and Accurate Determination of Life Extension for Offshore Units, in: Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Boutrot, J., Giorgiutti, Y., Rezende, F. and Barras, S. (2017b) Reliable and Accurate Determination of Life Extension for Offshore Units, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Bruun Ludvigsen, K., Kristian Jamt, L., Husteli, N. and Smogeli, Ø. (2016) Digital Twins for Design, Testing and Verification throughout a Vessel's Life Cycle. In: COMPIT '16 - 15th International Conference on Computer and IT Applications in the Maritime Industries.

Buck, B. H. and Langan, R. (eds) (2017) Aquaculture Perspective of Multi-use Sites in the Open Ocean: the Untapped Potential for Marine Resources in the Anthropocene. Cham: Springer International Publishing (Environment).

Cabos, C., Tietgen, B., Kang, B.S., Ha S. and Hulkkonen, T. (2015) 3D Ship Design from the Start - An Industry Case Study. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 257-268.

Cabos, C., Wolf, V. and Feiner, P. (2017) Remote Hull Surveys with Virtual Reality. In: Proceedings of the 16th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'17), Cardiff, pp. 444-453.

Cai, S., Sheng, L., Shan, P., Sun, Y., Liu, Y., and Liu, K., (2017) Application of New Common Structural Rules on Aframax Tankers, Tanker Structure Cooperative Forum 2016, Shipbuilders Meeting (http://www.tscforum.org/news/2016_list.aspx)

Canny, S. A. (2016) An Innovative Approach to Well Intervention and Workover Operations on Platforms With Limited Structural Capacity, in: Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Caprace. J. - D., Fu, G., Carrara, J. F., Remes, H. and Shin, S. B. (2017). A benchmark study of uncertainness in welding simulation, Marine Structures, Volume 56, pp 69-84.

Carlton, J., Jukes, P. and Choo, Y. S. (eds.) (2017) Encyclopedia of Maritime and Offshore Engineering. Chichester, UK: John Wiley & Sons, Ltd.

Carra, C., Potts, A. E., Johnstone, D. and Kilner, A. A. (2017) Determination of Rational Robustness Criteria for FPSO Design, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Carre, D., Mcarthur, L., Simpson, A., Zhang, P. and Vazquez, J. H. (2017) GSF Galaxy I Jackup Case Study for Optimizing Rig Move Performance in North Sea Using an Advanced Simulation Model, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Cepeda, M. A. F., Assis, L. F., Marujo, L. G. and Caprace, J. - D. (2017). Effects of slow steaming strategies on a ship fleet, Marine Systems & Ocean Technology, Volume 12 (3), September 2017, pp 178-186.

Chandrasekaran, S. (2015) Dynamic Analysis and Design of Offshore Structures. New York, NY: Springer Berlin Heidelberg (Ocean Engineering & Oceanography).

Chandrasekaran, S. (2016) Advanced Marine Structures. Boca Raton: CRC Press/Taylor & Francis Group.

Chandrasekaran, S. and Jain, A. K. (2017) Ocean Structures: Construction, Materials, and Operations. 1st Ed. Boca Raton, FL: CRC Press/Taylor & Francis Group.

Chang, G.-A. and Liu, M.-L. (2016) Simplified Spudcan and Soil Interaction Analysis for Jackup Touch-Down, in Future offshore technology and sustained reliability: 20th Offshore Symposium 2015: Houston, Texas, 17 February 2015. Red Hook, NY: SNAME/Curran Associates, Inc.

Chen, X., Kawamura, Y. and Okada, T. (2016). The Stochastic Finite Element Method based on Response Surface Methodology Considering Uncertainty in Shape of Structures. In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

Cherian L, Mathew T, Land J, Evans J. (2017) The design and analysis of a heavy transportation and jacket launch barge, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 213 221.

Choi, U., (2016). Impact of Harmonized CSR for oil tanker, Tanker Structure Cooperative Forum 2016, Shipbuilders Meeting (http://www.tscforum.org/news/2016_list.aspx)

Chopra, G. S. (2016) World's First Seabed Mining Vessel – Design Challenges, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Coello Coello, C. A., Lamont, G. B., and Van Veldhuizen, D. A., 2007, Evolutionary algorithms for solving multi-objective problems, Springer, New York.

Collette, M., Bronsart, R., Chen, Y., Erikstad, S.O., Georgiev, P., Giuglea, V., Jeong, H.K., Lazakis, I., Moro, L., Sekulski, Z., Sicchiero, M., Toyoda, M., Ventura, M. and Zanic, V. (2015). Design Methods, In: Proceedings of the 19th International Ship and Offshore Structures Congress (ISSC 2015), Cascais: CRC Press, pp. 459-518.

Constantinis, D. (2017) Operators, Class Societies targeting Safer, more Informative Hull Inspections, Offshore Magazine. Available at: http://www.offshore-mag.com/articles/print/volume-77/issue-8/productions-operations/operators-class-societies-targeting-safer-more-informative-hull-inspections.html, accessed on 03/11/2017..

Curtis, H. and Allan, P. (2015) A Finite Element Study of Boulder Interaction with Spudcans, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

Dae, H.K. and Paik, J.K. (2017). Ultimate limit state-based multi-objective optimum design technology for hull structural scantlings of merchant cargo ships. Ocean Engineering, Volume 129, pp. 318-334

Dai, L., Hu, H. and Chen, F. (2015) A GA-based heuristic approach for offshore structure construction spatial scheduling under uncertainty, Ships and Offshore Structures, 10(6), pp. 660–668.

Darie, I. and Rörup, J. (2017). Hull girder ultimate strength of container ships in oblique sea. In: Progress in the Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures (MARSTRUCT 2017). Lisbon: Taylor & Francis Group, pp. 225-233.

Darvishzadeh, T. and Sari, A. (2015) CFD Applications in Offshore Engineering, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

de Andrade, A. M. T., Vaz, C. E. M., Ribeiro, J., Lopreato, L. G. R. and do Nascimento, R. F. S. (2015) Offshore Production Units for Pre-Salt Projects, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

de Beer, T. (2017) Practical Aspects of Structural Integrity of FPSOs (keynote lecture), in. The 6th International Conference on Marine Structures (Marstruct 2017), Lisbon, Portugal.

de Haas, J. (2017) Ship Surveys: The Challenges Associated with Mega Container Ships, https://www.bmt.org/industry-insights/market-insights/ship-surveys-the-challenges-associated-with-mega-container-ships/, accessed on 10 November 2017.

Decò, A. and Frangopol, D. (2015). Real-time risk of ship structures integrating structural health monitoring data: Application to multi-objective optimal ship routing. Ocean Engineering, 96, pp.312-329.

Dessi D, Faiella E, Geiser J, Alley E, Dukes J. (2017) Design and structural testing of a physical model for wetdeck slamming analysis, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 3-12.

Dhillon, B. S. 2006 Maintainability, Maintenance, and Reliability for Engineers.

Dikis, K. and Lazakis, I. 2016. Dynamic Risk and Reliability Assessment of Ship Machinery and Equipment. Proceedings of the Twenty-sixth (2016) International Ocean and Polar Engineering Conference. 26 June-2 July 2016, Rhodes, Greece.

Dominguez R, Cali Y, García J. (2017) Forced vibration analysis of the hull girder by propeller excitation and rudder interaction, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 77-86.

Drimer, N., Moshkovich, Y. and Neuberg, O. (2017) 'A design method for planing hulls, considering hydro-elasticity and nonlinear dynamic structural response', Ships and Offshore Structures. Taylor & Francis (Ships and Offshore Structures), 12(7), pp. 971–979. doi: 10.1080/17445302.2016.1187362.

EARTO. (2014, April 30). Retrieved from The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations: http://www.earto.eu/publications1.html, accessed on: 01/11/2017

Ebrahimi, A., Brett, P. O., Agis, J. J. G., Brandt, U. and Gaspar, H. M. (2015) The Influence of Rule Changes on Design and Performance of Offshore Vessels – Myths Meet Reality, in. World Maritime Technology Conference, Providence, Rhode Island, USA: SNAME.

EC (2017). European Commission Technology Readiness Levels (TRL), http://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2016_2017/annexes/h2020-wp1617-annex-g-trl_en.pdf, accessed on: 02/11/2017

Ehlers S, Kujala P, Veitch B, et al. Scenario based risk management for Arctic shipping and operations[C]// ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2014: V010T07A006.

Ehlers, S., Kujala, P., Veitch, B., Khan, F. and Vanhatalo, J. (2014). Scenario based risk management for Arctic shipping and operations. In: Proceedings of ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. San Francisco: American Society of Mechanical Engineers, Volume 10.

El-Reedy, M. A. (2015) Marine Structural Design Calculations. 1st Ed. Oxford: Butterworth-Heinemann.

Engebretsen, E., Shu, Z. and Borgen, J. E. (2017) Estimating Hydrodynamic Sectional Loads for FPSOs Using Artificial Neural Networks, in. 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway: ASME, p. V001T01A048.

Engin, H. K., Khoa, H. D. V. and Jostad, H. P. (2015) Finite Element Analyses of Spudcan – Subsea Template Interaction during Jack-up Rig Installation, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

Fallah, S., Gavin, K. and Moradabadi, E. (2015) Estimation of Spudcan Penetration using a Probabilistic Eulerian Finite Element Analysis, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

Gallagher, D. and Rush, N. (2016a) Continued Service of Offshore Floating Structures, in Future offshore technology and sustained reliability: 20th Offshore Symposium 2015: Houston, Texas, 17 February 2015. Red Hook, NY: SNAME/Curran Associates, Inc.

Gallagher, D. and Rush, N. (2016b) Optimized Structural Integrity Management based in Design, in Future offshore technology and sustained reliability: 20th Offshore Symposium 2015: Houston, Texas, 17 February 2015. Red Hook, NY: SNAME/Curran Associates, Inc.

Garbatov Y, Georgiev P. (2017) Optimal design of stiffened plate subjected to combined stochastic loads, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 243 252.

Ghanem, R., Spanos, P. (1991). Stochastic Finite Elements: A Spectral Approach, New York: Springer-Verlag.

Gill, R. and Henzell, S. (2017) Design Once, Build Many, Offshore Engineer. Available at: http://www.oedigital.com/production/item/15885-design-once-build-many (Accessed: October 5, 2017).

Gkerekos, C., Lazakis, I. and Theotokatos, G. (2016) Ship Machinery Condition Monitoring using Vibration Data through Supervised Learning. International conference on Maritime Safety and Operations. 13-14 October 2016, Glasgow, U.K.

Gkerekos, C., Lazakis, I. and Theotokatos, G. (2017) Ship Machinery Condition Monitoring Using Performance Data Through Supervised Learning. RINA Smart Ships Technology. 24-25th January 2017, London, U.K.

Green P.L., Tygesen U.T. and Stevanovic N. (2016) Bayesian Modelling of Offshore Platforms. In: Atamturktur S., Schoenherr T., Moaveni B., Papadimitriou C. (eds) Model Validation and Uncertainty Quantification, Volume 3. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

Green4Sea (2017) World's first autonomous zero emissions ship planned for 2020, https://www.green4sea.com/worlds-first-autonomous-zero-emissions-ship-planned-for-2020/, accessed on 06/11/2017.

Greeson, T. D. and Waller, M. G. (2016) A Solution to Accurate Offshore Dimensional Control, in Emerging offshore technology and deepwater trends: 21st Offshore Symposium 2016: Houston, Texas, USA, 16 February 2016. Red Hook, NY: SNAME/Curran Associates, Inc.

Ha, Y. S., Park, J. S., Koo, J. B., Cho, B. J., Ma, K. Y. and Jang, K. B. (2016) Engineering Establishment of Living Quarters for Jack-Up Rig Structures, in. 35th International Conference on Ocean, Offshore & Arctic Engineering, Busan, South Korea: ASME, p. V003T02A079.

Haïdar, T. (2016) Time and Tide Wait for No Man: The Importance of Structural Integrity. Bentley.

Hendriks, S., Claassen, L. and Chalkias, D. (2015) Magellan Class Drillship: Designing the Rig of the Future, in. Offshore Technology Conference, Brazil: Society of Petroleum Engineers.

Hendriks, S., Man, P. de, Zijderveld, G. and Diemen, C. van (2017) Euryale Moonpool - Innovative Naval Architecture Design Enables Full Dual Drilling Accessibility on a Drillship, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Hernæs, S. and Aas, T. (2015) An Alternative Approach to 50 Years Design Life, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Hodapp, D., Ma, W., Wisch, D. and Lee, M.-Y. (2017) Improving Cost Efficiency in Floating Production Facilities: Semi-Submersible Design Standardization, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

IACS (2006a) Common Structural Rules for Double Hull Oil Tankers, January 2006.

IACS (2006b) Common Structural Rules for Bulk Carriers, January 2006.

IACS (2012a) Common Structural Rules for Bulk Carriers, July 2012.

IACS (2012b) Common Structural Rules for Double Hull Oil Tankers, July 2012.

IACS (2014). Common Structure Rules for Bulk Carriers and Oil Tankers 1 JAN 2014, International Association of Classification Societies

IACS (2016). Private communication, IACS, August 2016.

IACS (2006a) Common Structure Rules for Bulk Carriers, International Association of Classification Societies

IACS (2006b) Common Structure Rules for Oil Tankers, International Association of Classification Societies

IACS (2017). Common Structure Rules for Bulk Carriers and Oil Tankers 01 JAN 2017 version, International Association of Classification Societies

Im, H.I., Vladimir, N., Malenica, Š., Cho, D.S., Ryu, H.R. and De Lauzon, J. (2016) Ultimate strength check of HHI SkyBenchTM ultra large container ship considering slamming and whipping effects, In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

IMO (2009a) Prevention of Air Pollution From Ships, Marine Environment Protection Committee, MEPC 59/4/47, 22 May 2009.

IMO (2009b) Second IMO GHG Study 2009, International Maritime Organization (IMO), London, UK, April 2009; Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K.

IMO (2013) MSC.1/Circ.1455, Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments. London: IMO, p. 51.

IMO (2014) Reduction of GHG Emissions From Ships, Third IMO GHG Study 2014 – Final Report, Marine Environment Protection, Committee, MEPC 67/Inf.3, 25 July 2014.

IMO (2017) EEDI - rational, safe and effective. International Maritime Organisation (IMO), http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/EEDI.aspx, accessed on 30 August 2017.

IMO MSC.1/Circ.1455 , Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments [Z].2013.

INCASS (2014a) Deliverable D4.2 Stakeholders' data requirements. WP4 - Machinery & Equipment Modelling & Analysis. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

INCASS (2014b) Deliverable D5.3 Database: Structural and Machinery Interface. WP5 - Database Development & Implementation. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

INCASS (2014c) Deliverable D5.4 Data Exchange. WP5 - Database Development & Implementation. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

INCASS (2015a) Deliverable D2.1 Technological tools and components for the conduction of automated or supported survey activities. WP2 - Intelligent Monitoring Systems. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

INCASS (2015b) Deliverable D2.2 Integrated tool for visual data analysis. WP2 - Intelligent Monitoring Systems. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

INCASS (2016a) Deliverable D5.5 Ship shore communications. WP5 - Database Development & Implementation. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

INCASS (2016b) Deliverable D5.6 Central database delivery. WP5 - Database Development & Implementation. Inspection Capabilities for Enhanced Ship Safety EC FP7 Project.

ISSC2003 (2003) In 15th International Ship and Offshore Structures Congress (ISSC) 2003 Report, Commettee IV.2.

ISSC2009 (2009) In 15th International Ship and Offshore Structures Congress (ISSC) 2003 Report, Commettee IV.2.

ISSC2012 (2012) In 18th International Ship and Offshore Structures Congress (ISSC) 2012 Report, Commettee IV.2.

ISSC2015. (2015). In 19th International Ship and Offshore Structures Congress (ISSC) 2015 Report, Commettee IV.2.

Janssen, J., Hofstede, H., Hoogeveen, M. and Wu, J.-F. (2016) Improvement of Jack-Up Operating Capability using add-on Spudcans, in Emerging offshore technology and deepwater trends: 21st Offshore Symposium 2016: Houston, Texas, USA, 16 February 2016. Red Hook, NY: SNAME/Curran Associates, Inc.

Ji, Z., Gang, C., Jian, M., Yuhan, W. and Wei, Z. (2015) The Study on Hull Structure Strength Analysis and Opening Calculation of CJ46 Jack-Up Drilling Unit, in. 34th International Conference on Ocean, Offshore and Arctic Engineering, St. John’s, Newfoundland, Canada: ASME, p. V007T06A066.

Jin, R., Chen, W., and Simpson, T. W. (2001) "Comparative studies of metamodelling techniques under multiple modelling criteria," Structural and Multidisciplinary Optimization, 23(1), pp. 1-13.

Jostad, H. P., Torgersrud, Ø., Engin, H. K. and Hofstede, H. (2015) A FE procedure for calculation of fixity of jack-up foundations with skirts using cyclic strain contour diagrams, in. 16th International Conference: The Jack-Up Platform, London.

Joung, T., Choi, H., Lee, S., Kim, J., Lee J., Oh T. (2017) A Study on the Global Buckling Analysis and Structural Effectiveness of Connection Parts of Pressure vessel, ICSOS 2017: Proceedings of the International Conference on Ships and Offshore Structures, Sören Ehlers & Jeom Paik & Young Bai (Eds.), Shenzhen, China, 11-13 September, 2017.

Joung T., Park B., Choung C. (2017) Performance Test Analysis and Structural Safety Assessment by using Reliability Analysis, ICSOS 2017: Proceedings of the International Conference on Ships and Offshore Structures, Sören Ehlers & Jeom Paik & Young Bai (Eds.), Shenzhen, China, 11-13 September, 2017.

Jung, J. J., Lee, I. H., Chung, B. Y., Kim, S. E. and Kim, S. H. (2017) Standardization of FPSO Hull with 2MMbbls Storage Capacity for West Africa, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Kefal, A. and Oterkus, E. (2017) Shape and Stress Sensing of Offshore Structures by using Inverse Finite Element Method, in. The 6th International Conference on Marine Structures (Marstruct 2017), Lisbon, Portugal: CRC Press/Taylor & Francis Group.

Kefal, A. and Oterkus, E. (2017). Shape and stress sensing of offshore structures by using inverse finite element method. In: MARSTRUCT 2017, the 6th International Conference on Marine Structures. Taylor & Francis Group.

Kefal, A. and Oterkus, E. (2016) Displacement and stress monitoring of a chemical tanker based on inverse finite element method. Ocean Engineering, 112, pp.33-46.

Kefal, A. and Oterkus, E. (2016) Displacement and stress monitoring of a Panamax containership using inverse finite element method. Ocean Engineering, 119, pp.16-29.

Kemp, D. (2016) A Risk Based Approach to Managing the Integrity of Aging Production Facilities in the Gulf of Mexico, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Kheireddine, H., Chen, D. and Timms, J. (2016) Introducing Holistic Approach for the Design and Operation of FLNG Development, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Khurana, S., D'Souza, R., Yanosek, K., Christ, F. and Meeks, P. (2017) Bringing Upstream Projects to Final Investment Decision, in. Offshore Technology Conference.

Kim, D. H. and Paik, J. K. (2017) 'Ultimate limit state-based multi-objective optimum design technology for hull structural scantlings of merchant cargo ships', Ocean Engineering. (Ocean Engineering), 129(Supplement C), pp. 318–334. doi: https://doi.org/10.1016/j.oceaneng.2016.11.033.

Kim, J. D. and Jang, B.-S. (2016) Application of Multi-Objective Optimization for TLP Considering Hull-Form and Tendon System, Ocean Engineering, 116, pp. 142–156.

Kim, J. W., Jang, H., Kyoung, J., Baquet, A. and O'Sullivan, J. (2015) CFD-Based Numerical Wave Basin for Offshore Floater Design, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Kim, J.-D. and Jang, B.-S. (2016) Application of the Global Optimization Method to the Preliminary Design of Tension Leg Platforms, in. 35th International Conference on Ocean, Offshore & Arctic Engineering, Busan, South Korea: ASME, p. V003T02A077.

Kim, S. P., Petricic, M., Xie, G., Wu, G. and Seah, R. (2016) Strength and Fatigue Assessment of Extended Bilge Keels for FPSO/FLNG, in. Houston, Texas, USA: Offshore Technology Conference.

Kim, S.-K., Roh, M.-I. and Kim, K.-S. (2017) Arrangement Method of Offshore Topside Based on an Expert System and Optimization Technique, Journal of Offshore Mechanics and Arctic Engineering, 139(2), p. 021302.

Kitchen, P. (2015) Process Support and Marine Systems in the Hull - Innovation Meets Regulation, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Knight J. (2017) Rapid, early-stage ultimate limit state structural design for multihulls, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 269 275.

Knight, J. T., Collette, M. D. and Singer, D. J. (2015) 'Design for flexibility: Evaluating the option to extend service life in preliminary structural design', Ocean Engineering. (Ocean Engineering), 96 (Supplement C), pp. 68–78. doi: https://doi.org/10.1016/j.oceaneng.2014.12.035 .

Knodt, S., Kleinen, T., Dornieden, C., Lorscheidt, J., Bjørneklett, B. and Mitzlaff, A. (2016) Development and Engineering of Offshore Mining Systems - State of the Art and Future Perspectives, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Ko, Y., Kmi, S. and Paik, J. (2017) Contribution of a deformable striking-ship structure to the structural crashworthiness of ship-ship collisions, ICSOS 2017: Proceedings of the International Conference on Ships and Offshore Structures, Sören Ehlers & Jeom Paik & Young Bai (Eds.), Shenzhen, China, 11-13 September, 2017.

Koch, T., Smith, M. and Tanneberger, K. (2015) Improving Machinery & Equipment Life Cycle Management Processes. In: COMPIT '15 - 14th International Conference on Computer and IT Applications in the Maritime Industries. Volker Bertram.

Koelman, H., van der Zee, J. and de Jonge, T. (2015) A Virtual Single Ship-Design System Composed of Multiple Independent Components, In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 126-134.

Kolios A.J., Rodriguez-Tsouroukdissian, A. and Salonitis K. (2016) Multi-criteria decision analysis of offshore wind turbines support structures under stochastic inputs. Ships and Offshore Structures. Volume 11 (1), pp 38-49.

Konovessis, D., Cai, W. and Vassalos, D. (2013) Development of Bayesian Network Models for Risk-Based Ship Design[J]. Journal of Marine Science and Application, 2013, 12(2):140-151.

Konovessis, D., Cai, W. and Vassalos, D. (2013) Development of Bayesian Network Models for Risk-Based Ship Design. Journal of Marine Science and Application, Volume 12 (2), pp. 140-151.

Koole, T. and van der Kraan, M. (2015) Modern Jack-Ups and their Dynamic Behaviour, in. 15th International Conference: The Jack-Up Platform, London.

Korbetis, G., Chatzimoisiadis, S. and Drougkas, D. (2015) Automated Interoperability from Concept Design to Multidisciplinary FE Analysis. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 116-125

Korbetis, K., Chatzimoisiadis, S. and Drougkas, D. (2017) EPLYSIS, a New Solver for Finite Element Analisys. In: Proceedings of the 16th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'17), Cardiff, pp. 190-200.

Koroglu, S.A. and Ergin, A. (2016) A decomposition method for surrogate models of large scale structures, Journal of Marine Science and Technology, Volume 21 (2), pp 325–333

Kwon, S., Kim, B.C., Mun, D. and Han, S. (2015) Simplification of feature-based 3D CAD assembly data of ship and offshore equipment using quantitative evaluation metrics. Computer-Aided Design, 59, pp.140-154.

Larkins, D. Waldie, M. and Morais, D. (2015) Utilizing a Single 3D Product Model throughout the Design Process. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp: 465-472.

Latarche, M. (2017). Class Societies update CSR software suites. The Naval Architect. March 2017 pp. 36-37

Lee, J.-C., Shin, S.-C. and Kim, S.-Y. (2015) "An optimal design of wind turbine and ship structure based on neuro-response surface method" Int. J. Nav. Archit. Ocean Eng. 7:750~769

Lee, H. D., Son, J.-S., Kim, I.-H. and Jeong, H.-N. (2017) Offshore Standardization Process and Criteria Development for EPC Project, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Lee, J. M., Kim, Y. H., Hossain, M. S., Hu, Y., Won, J. H., Park, J. S. and Jun, M. J. (2015) Use of Novel Spudcan Shapes for Mitigating Punch-Through Hazards, in. 15th International Conference: The Jack-Up Platform, London.

Lee, J., Sung, S., Kim, S., Kraus, A. and Lee, J. (2015) An optimal sub-structure for a TLP-type wind turbine based on neuro-response surface method, Journal of Marine Science and Technology, Volume 20 (4), pp 604–616.

Leon, A. (2017) Managing Maintenance, Offshore Engineer. Available at: http://www.oedigital.com/technology/software/item/14355-managing-maintenance.

Levanger, H., Notaro, G. and Hareide, O. J. (2016) Collision Response and Residual Strength of Jack-up Structure, in. 13th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS'2016), Copenhagen, Denmark.

Lin, L. and Ong, M. C. (2017) A Preliminary Study of a Rigid Semi-Submersible Fish Farm for Open Seas, in. 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway: ASME, p. V009T12A044.

Lin, L., Jiang, Z. and Ong, M. C. (2017) A Preliminary Study of a Vessel-Shaped Offshore Fish Farm Concept, in. 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway: ASME, p. V006T05A006.

Lindner, H., Schenk, S., Bronsart, R., Ebeling, B., Frömming, K. and Kluwe, F. (2015) A Modular System Architecture for the Early Ship Design by Combining a 3D-CAD System with a Product Data Management System, In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp. 135-146.

Lindstad, H., Eskeland, G. S., Psaraftis, H., Sandaas, I. and Strømman, A. H. (2015) 'Maritime shipping and emissions: A three-layered, damage-based approach', Ocean Engineering. (Ocean Engineering), 110(Part B), pp. 94–101. doi: https://doi.org/10.1016/j.oceaneng.2015.09.029.

Lipman, R. and Lubell, J. (2015) Conformance checking of PMI representation in CAD model STEP data exchange files. Computer-Aided Design, 66, pp. 14-23.

Liu, S., Hua, D., Machado, C. and Wu, J.-F. (2016) Class Approach for Life Extension Process of Floating Production Installations, in Emerging offshore technology and deepwater trends: 21st Offshore Symposium 2016: Houston, Texas, USA, 16 February 2016. Red Hook, NY: SNAME/Curran Associates, Inc.

Ma Ming, Brown, A., McNatt, T. and Freimuth, J., (2016) Naval ship hull structural scantling optimization by reducing weight, increasing safety and lowering verticalcenter of gravity, Marine Technology Conference, SNAME, Seattle, USA.

Ma, C., Oka, M., and Iijima, K. (2017) A numerical simulation for coupling behavior between smoothed particle hydrodynamics and structural finite element method. In: Progress in the Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures (MARSTRUCT 2017). Lisbon: Taylor & Francis Group, pp. 21-28.

Maes, M. A. and Dann, M. R. (2017) Freak Events, Black Swans, and Unknowable Unknowns: Impact on Risk-Based Design[C]// International Probabilistic Workshop. 2017.

Maes, M.A. and Dann, M.R. (2017) Freak Events, Black Swans, and Unknowable Unknowns: Impact on Risk-Based Design. In: Proceedings of the 14th International Probabilistic Workshop, Ghent: Springer, pp. 15-32.

Majed, A., Mansour, A., Chinello, L. and Wan, Y. (2016) A Dynamic Substructuring Approach to Improved Global Structural Dynamic And Stress Analysis of Topside/Hull Systems, in Emerging offshore technology and deepwater trends: 21st Offshore Symposium 2016: Houston, Texas, USA, 16 February 2016. Red Hook, NY: SNAME/Curran Associates, Inc.

Marinic-Kragic, I., Vucina, D. and Curkovic, M. (2016) 'Efficient shape parameterization method for multidisciplinary global optimization and application to integrated ship hull shape optimization workflow', Computer-Aided Design. (Computer-Aided Design), 80(Supplement C), pp. 61–75. doi: https://doi.org/10.1016/j.cad.2016.08.001.

Marinić-Kragić, I., Vučina, D. and Ćurković, M. (2016) Efficient shape parameterization method for multidisciplinary global optimization and application to integrated ship hull shape optimization workflow, Computer-Aided Design, Volume 80, pp 61-75.

Marques, C. H., Belchior, C. R. P., Caprace, J. - D. (2017a). A model to optimise the selection of marine dual-fuel low-speed diesel engines, Marine Systems & Ocean Technology, Volume 12 (3), September 2017, pp 138-149.

Marques, C. H., Belchior, C. R. P., Caprace, J. - D. (2017b). An approach to optimise the selection of Lng carriers' propulsion system, Engenharia Térmica (Thermal Engineering), Volume 16 (1), June 2017, pp 37-45.

Maslin, E. (2017) Neural Networking by Design, Offshore Engineer. Available at: http://www.oedigital.com/component/k2/item/14810-neural-networking-by-design.

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Azman, N. U. and Najafian, G. (2016) Reliability-Based Design and Assessment for Lifetime Extension of Ageing Offshore Structures, in. 35th International Conference on Ocean, Offshore & Arctic Engineering, Busan, South Korea: ASME, p. V003T02A044.

McLaren, A. R. (2017) An Investigation into the Global Sway Buckling Failure mode of Jack-up Units and its Impact on the Calculation of Effective Length Factors for Individual Legs, in. 16th International Conference: The Jack-Up Platform, London.

Mendonça Santos, J. and Alves, C. (2016) A Wind Heeling Moment Curve for Ship-shaped MODU early Design Stability Considerations, in Maritime Technology and Engineering III: Proceedings of the 3rd International Conference on Maritime Technology and Engineering (MARTECH 2016, Lisbon, Portugal, 4-6 July 2016). Guedes Soares & Santos (Eds). Taylor & Francis Group.

Moan, T. (2015) Official discussion, Committee IV.2, Design Methods ISSC 2015. In 19th International Ship and Offshore Structures Congress (pp. 995-1008). Cascais, Portugal.

Mobbs, B. and Stiff, J. J. (2017) Effective Shear Areas of Jack-up Chords – Development of a Logical Approach to Assessment, in. 16th International Conference: The Jack-Up Platform, London.

Moe, A. M. and Laranjinha, M. (2017) Design Methodology for Converting a MODU into a FPU, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Mohrman, E.S.A. and Lawler III, E.E. (2011) Research for Theory and Practice: Framing the Chalenge. In E. S.A. Mohram and E.E.Lawler III, Useful Research: Advancing Theory and Practice (pp. 9 -35). San Francisco: Berrett-Koehler.

Moir, C. (2016) Online Monitoring System Helps Assess Integrity of North Sea Platform, Offshore Magazine. Available at: http://www.offshore-mag.com/articles/print/volume-76/issue-11/european-supplement/online-monitoring-system-helps-assess-integrity-of-north-sea-platform.html.

Moir, S. (2017) Improving Offshore Inspection Efficiency through UAV Inspections, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Moon, S.C., Jeong, S., Song, H.C. and Na, S.S. (2016) Development of automated algorithm of integrated structural design system based on CSR-H for bulk carrier. In: Proceedings of the 29th Asian-Pacific Technical Exchange and Advisory Meeting on Marine Structures (TEAM2015), Vladivostock.

Moore, B., Easton, A., Cabrera, J., Webb, C. and George, B. (2017) Stones Development: Turritella FPSO - Design and Fabrication of the World's Deepest Producing Unit, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Morais, D., Waldie, M. and Danese, N. (2016) Open Architecture Applications: The Key to Best-of-Breed Solutions. In: Proceedings of the 15th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'16), Lecce, pp 223-233.

Morais, D., Waldie, M. and Danese, N. (2016) Open Architecture Applications: The Key to Best-of-Breed Solutions. In: COMPIT '16 - 15th International Conference on Computer and IT Applications in the Maritime Industries. Volker Bertram.

Morais, D., Waldie, M. and Darren, L. (2017) The evolution of Virtual Reality in Shipbuilding. In: Proceedings of the 16th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'17), Cardiff, pp. 128-138.

Morais, D., Waldie, M. and Larkins, D. (2015) Completely Rethinking Weld Management: Leveraging 3D Models and Visualization. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 382-393

Morandi, A. (2017) Challenges in the Structural Design of Jack-up and Semi-submersible Rigs (keynote lecture), in. The 6th International Conference on Marine Structures (Marstruct 2017), Lisbon, Portugal.

Na Seung-Soo, Karr Dale G. (2016) Development of Pareto strategy multi-objective function method for the optimum design of ship structures, International Journal of Naval Architecture and Ocean Engineering, Available online 24 October 2016, ISSN 2092-6782, http://dx.doi.org/10.1016/j.ijnaoe.2016.06.001

Naruse, Y., and Kawamura, Y. (2015) A comparison of structural reliability of ultimate strength of bulk carriers before and after the effectuation of CSR. In: Proceedings of the 29th Asian-Pacific Technical Exchange and Advisory Meeting on Marine Structures (TEAM2015), Vladivostock.

Noh Y, Chang K, Seo Y, et al. Risk-based determination of design pressure of LNG fuel storage tanks based on dynamic process simulation combined with Monte Carlo method [J]. Reliability Engineering & System Safety, 2014, 129:76-82.

Noh, Y., Chang, K., Seo, Y. and Chang D. (2014) Risk-based determination of design pressure of LNG fuel storage tanks based on dynamic process simulation combined with Monte Carlo method. Reliability Engineering & System Safety, Volume 129, pp. 76-82.

Nunes, G. C., Lopreato, L. G. R., Da Silva Ferreira, M. D. A., Vilamea, E. M. and De Oliveira, G. P. H. A. (2016) Petrobras Approach to FPSO Cost Reduction, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Odeskaug, L. (2015) The Cylindrical Hull Concept for FLNG Application, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

OECD (2015) OECD Science. Technology and Industry Scoreboard 2015. OECD.

OECD/ITF (OECD International Transport Forum) (2015) The Impact of Mega-ships, May 2015.

Oh, M.-H., Boo, S.-H., Lee, P.-S., Kim, J.-M., Moon, J.-S. and Sim, W.-S. (2017) Applications of the Static Condensation Technique to Nonlinear Structural Analysis of Floating Offshore Structures, in. 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway: ASME, p. V03BT02A031.

Paboeuf, S., Le Sourne, H., Brochard, K. and Besnard, N. (2015) A damage assessment tool in ship collisions. In: Proceedings of RINA, Royal Institution of Naval Architects - Damaged Ship III, International Conference on Damaged Ship III. London, pp. 21-31

Pallanich, J. (2017) Flexible Floater, Upstream Online, 3 April. Available at: http://www.upstreamonline.com/upstreamtechnology/1236053/flexible-floater.

Parunov J, Rudan S, Gledić I, Primorac B. (2017) Finite element study of residual ultimate strength of a double hull oil tanker damaged in collision and subjected to bi-axial bending, ICSOS 2017: Proceedings of the International Conference on Ships and Offshore Structures, Sören Ehlers & Jeom Paik & Young Bai (Eds.), Shenzhen, China, 11-13 September, 2017.

Pendlebury, D. A. (2008) WHITE PAPER Using Bibliometrics in Evaluating Research. Thomson Reuters.

Peschmann, J., von Selle, H., Jankowski, J., Horn, G. and Arima, T. (2017) IACS common structural rules as an element of IMO goal based standards for bulk carriers and oil tankers, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 297-304.

Pessoa, J. M. and Moe, A. M. (2017) Air Gap on Semisubmersible MODUs Under DNVGL Class - Current & Future Design Practice, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Pillai, A.C., Chick, J., Johanning, L., Khorasanchi, M. and Pelissier, S. (2016) Optimization of Offshore Wind Farms Using a Genetic Algorithm. International Journal of Offshore and Polar Engineering, Volume 26 (3), pp. 225–234.

Pire, T., Echeverry, S., Rigo, P., Buldgen, L. and Le Sourne, H. (2017) Validation of a simplified method for the crashworthiness of offshore wind turbine jackets using finite elements simulations. In: Progress in the Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures (MARSTRUCT 2017). Lisbon: Taylor & Francis Group, pp. 497-505.

Poll, P., Park, Y. C., Converse, R., Godfrey, D. and Gian, M. (2015) Gulfstar - Structural Design of the Classic Spar Hull for Improved Constructability, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Portella, R. B. and de Souza Lima, H. A. (2016) Cessão Onerosa FPSOs - Challenges and Achievements Conducting Four Simultaneous Hull Conversion Designs, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Pradillon, J., Chen, C., Collette, M., Czaban, Z.J., Erikstad, S.O., Giuglea, V., Jiang, X., Rigo, P., Roland, F., Takaoka, Y. and Zanic, V. (2012) Design Methods, In: Proceedings of the 18th International Ship and Offshore Structures Congress (ISSC 2012), Rostock, pp: 507-576.

Pradillon, J.Y., Chen, C.P., Collette, M., Czaban, J.Z., Erikstad, S.O., Giuglea, V., Jiang, X., Rigo, P., Roland, F., Takaoka, Y., and Zanic, V. (2012). Design Methods. In: Proceedings of the 18th International Ship and Offshore Structures Congress (ISSC 2012). Vol. 1 pp. 507-576. Rostock.

Praetorius, G., Graziano, A., Schröder-Hinrichs. J. U. and Baldauf, M. (2017) FRAM in FSA—Introducing a Function-Based Approach to the Formal Safety Assessment Framework[M]// Advances in Human Aspects of Transportation. Springer International Publishing, 2017.

Praetorius, G., Graziano, A., Schröder-Hinrichs, J.U. and Baldauf, M. (2017). FRAM in FSA—Introducing a Function-Based Approach to the Formal Safety Assessment Framework. In: N. Stanton, S. Landry, G. Di Bucchianico G. and A. Vallicelli, eds, Advances in Human Aspects of Transportation. Advances in Intelligent Systems and Computing, Volume 484. Springer, Cham

Proceedings of the 2003 ISSC (2003), 14th International Ship and Offshore Structures Congress

PRS (2017) Private communication, Polish Register of Shipping, (PRS), September 2017.

Raikunen J, (2015) "Optimization approach for passenger ship structures using Finite Element Method", M.Sc. thesis, Aalto University, School of Engineering, 2015.

Raithatha, A. and Stonor, R. W. P. (2015) Efficient Non-linear Dynamic Analysis of Elevated Jack-Ups under Vessel Impact, in. 15th International Conference: The Jack-Up Platform, London.

Ravina, E. (2017). Concept design of an autonomous mechatronic unit for inspection of holds. In: Proceedings of the 6th International Conference On Marine Structures (Marstruct 2017). London: Taylor & Francis Group.

Rezende, F. C. and Barcarolo, D. (2017) Moonpool Effects on the Structural Assessment of Drillships, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Rodrigues J, Guedes Soares C. (2017) Still water vertical bending moment in a flooding damaged ship, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 35-42.

Rolls-Royce (2017) Autonomous Ships. The next step, http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/rr-ship-intel-aawa-8pg.pdf, accessed on 6 November 2017.

Romanoff Jani, Jasmin Jelovica, Eero Avi, Bruno Reinaldo Goncalves, Mihkel Körgesaar, Joni Raikunen, Heikki Remes, Ari Niemelä, JN Reddy and Petri Varsta, (2016), Use of an Equivalent Single Layer Plate Theory in Ship Structural Design, PRADS 2016, Copenhagen, September 2016

Romanoff, J., Jelovica, J., Avi, E., Goncalves, B.R., Körgesaar, M., Raikunen, J., Remes, H., Niemelä, A., Reddy, J.N. and Varsta P. (2016). Use of an Equivalent Single Layer Plate Theory in Ship Structural Design. In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

Rörup, J., Maciolowski, B. and Darie, I. (2016). FE-based strength analysis of ship structures for a more advanced class approval. In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

Rosen, J., Potts, A., Sincock, P., Carra, C., Kilner, A., Kriznic, P. and Gumley, J. (2016) Novel Methods for Asset Integrity Management in a Low Oil-Price Environment, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Roth, M. (2016). Recording As-Built via an Open and Lightweight Solution Supplemented by a Process Evaluation Model. In: COMPIT '16 - 15th International Conference on Computer and IT Applications in the Maritime Industries. Volker Bertram.

Scherl, G. and Sodomaco, P. (2016) Two are Better than one a Hydrodynamic-Structural Case Study, in Future offshore technology and sustained reliability: 20th Offshore Symposium 2015: Houston, Texas, 17 February 2015. Red Hook, NY: SNAME/Curran Associates, Inc.

Seo, H., Park, S., and Jung, J. (2017). Study on Fatigue Strength for Tank Structures subject to Harmonized CSR, Tanker Structure Cooperative Forum 2016, Shipbuilders Meeting

Seo, J. K. and Kim, D. E. (2015) An Efficient Erection Simulation Methodology for the Modular Construction of Offshore Platform Based on Points Cloud Data, in. 34th International Conference on Ocean, Offshore and Arctic Engineering, St. John's, Newfoundland, Canada: ASME, p. V001T01A002.

Shen, J., Liu, F., Li, H., Xu, L. and Liang, B., (2015). Assessment of the damages occurring between two adjacent measurements for an aging offshore platform. Ocean Engineering, 109, pp.372-380.

Shibasaki K. (2016) Shipbuilding industry's perspective on the new IACS Common Structural Rules. In: Tanker Structure Cooperative Forum 2016, Shipbuilders Meeting. Busan. Available at: http://www.tscforum.org/news/2016_list.aspx

Shibasaki, K. (2015) Shipbuilding Industry's perspective on the new IACS Common Structural Rules. In: Proceedings of the 7th meeting of the Tanker Structure Co-operative Forum (TSCF2016). Busan. (http://www.tscforum.org/news/2016_list.aspx)

Shibasaki, K. (2016) Shipbuilding industry's perspective on the new IACS Common Structural Rules, TSCF (Tanker Structure Co-operative Forum) 2016 SBM (Shipbuilders Meeting), 26 - 27 October 2016, Korea.

Shiptec China (2016). 12th International Shipbuilding, Marine Equipment and Offshore Engineering Exhibition for China, http://www.chinaexhibition.com/trade_events/7071-Shiptec_China_2016_12th_International_Shipbuilding,_Marine_Equipment_and_Offshore_Engineering_Exhibition_for_China.html, accessed on 03/11/2017.

Skafte, A., Kristoffersen, J., Vestermark, J., Tygesen, U.T. and Brincker, R., 2017. Experimental study of strain prediction on wave induced structures using modal decomposition and quasi static Ritz vectors. Engineering Structures, 136, pp.261-276.

Skafte, A., Tygesen, U.T. and Brincker, R., 2014. Expansion of mode shapes and responses on the offshore platform Valdemar. In Dynamics of Civil Structures, Volume 4 (pp. 35-41). Springer, Cham.

Skau, K. S., Torgersrud, Ø., Jostad, H. P., Hofstede, H. and Hermans, S. (2015) Linear and Nonlinear Foundation Response in Dynamic Analyses of Jack-up Structures, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International

Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

So, H.Y., Bae, M.N., and Min, D.K. (2017). MR. Tanker with Harmonized CSR, Tanker Structure Cooperative Forum 2016, Shipbuilders Meeting (http://www.tscforum.org/news/2016_list.aspx)

Son, M., Gyun Park, H., Lee, J.Y., Lee, J. Jong-oh Kim, J. and Woo, J. (2016). Development of Auto FE Modeling for enhancement of the productivity in modeling based on CSR-H. In: Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures (PRADS 2016), Copenhagen.

Son, M., Park, H.G., Lee, J.Y., Lee, J., Kim, J., and Woo, J. (2016) Development of Auto FE Modeling for enhancement of the productivity in modeling based on CSR-H. Proceedings of the 13th PRADS2016, Copenhagen.

Stilhammer, J., Steenbock, C. and Bohm, M. (2015). A Complete CAE Process for Structural Design in Shipbuilding, In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 406-417.

Stone, K. and McNatt, T. (2017). Ship hull scantling optimization. In: Progress in the Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures (MARSTRUCT 2017). Lisbon: Taylor & Francis Group, pp. 203-211.

Sugita, S. and Suzuki H. (2016). A study on TLP hull sizing by utilizing optimization algorithm. Journal of Marine Science and Technology, Volume 21 (4), pp. 611–623

Taheri, A., Lazakis, I. and Koch, T., 2015, September. An innovative machinery data management system for ships using a catalogue data model. In 16th International Congress of the International Maritime Association of the Mediterranean, IMAM 2015.

Talib, J. H. and Germinder, B. (2016) Game-Changing Floating LNG Solutions, in. Houston, Texas, USA: Offshore Technology Conference.

Tanaka, S. and Takano, K. (2017) Next Generation Hull-Platform "Noah-FPSO Hull" Based On Modular Design And Construction Concept, in. 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway: ASME, p. V001T01A063.

Taylor, J. D., Foret, R. and Buchert, S. (2015) SS Delta House - Topsides Design Philosophy, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Thakker, B. (2015). Portals in Shipbuilding. In: COMPIT '15 - 14th International Conference on Computer and IT Applications in the Maritime. Volker Bertram.

The Economist (2013) When giants slow down, Jul 27th 2013, https://www.economist.com/news/briefing/21582257-most-dramatic-and-disruptive-period-emerging-market-growth-world-has-ever-seen, accessed on 10 November 2017.

The Financial Times (2015) OECD cuts world growth forecast, https://www.ft.com/content/4ac6334e-86cd-11e5-90de-f44762bf9896, accessed on 10 November 2017.

The Maritime Executive (2017) CMA CGM Confirms Order for 22,000 TEU Mega-Ships, https://maritime-executive.com/article/cma-cgm-confirms-order-for-22000-teu-mega-ships, accessed on 6 November 2017.

The Naval Architect (2015). 3D design approach saves time and money, Volume February, pp. 50-51

The Naval Architect (2016) Collaboration not competition is the new 3D reality, Volume April, pp. 32-34

The Naval Architect (2016) Smart connected & Bigger – IT for Ships, Volume April, pp. 24-26

Tho, K. K., Chan, N. and Paisley, J. (2015) Comparison of Coupled and Decoupled Approaches to Spudcan-Pile Interaction, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

Tho, K. K., Chan, N., Zhou, Y., Liu, J. and Zhou, S. (2015) Case Study of Spudcan Re-penetration Analysis using Large Defirmation Finite Element Approach, in. 15th International Conference: The Jack-Up Platform, London.

Thomson, D. and Gordon, A. (2016). Maritime Asset Visualisation. In: COMPIT '16 - 15th International Conference on Computer and IT Applications in the Maritime Industries. Volker Bertram.

Tian, Y., Zheng, T., Zhou, T. and Cassidy, M. J. (2016) A New Method to Investigate the Failure Envelopes of Offshore Foundations, in. 35th International Conference on Ocean, Offshore & Arctic Engineering, Busan, South Korea: ASME, p. V001T10A002.

Tian, Z. K., Kirkland, B., Radanovic, B. and Dasilva, O. (2017) Opti® Series Production Semi-Submersible Hull Sizing Process, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Tippee, J. (2017) Standardization JIP Aims to Improve Design and Construction Efficiencies, Offshore Magazine. Available at: http://www.offshore-mag.com/articles/print/volume-77/issue-3/asia-pacific/standardization-jip-aims-to-improve-design-and-construction-efficiencies.html, accessed on 03/11/2017.

Um T.-S. and Roh M.-I. (2015) "Optimal dimension design of a hatch cover for lightening a bulk carrier" Int. J. Nav. Archit. Ocean Eng. (2015) 7:270~287

Un-Chul Choi. (2016) Impact of Harmonized CSR for oil tanker, Tanker Structure Cooperative Forum 2016, Shipbuilders Meeting,26-27 October 2016, Busan, South Korea

University of Ottawa. (2017). 21st century science overload, http://www.cdnsciencepub.com/blog/21st-century-science-overload.aspx, accessed on 03/11/2017.

US TRB. (2017). US Transportation Research Board, http://prp.trb.org, accessed on 3/11/2017

van Lukas, U., Ruth, T., Deistung, E. and Huber, L. (2015). Leveraging the Potential of 3D Data in the Ship Lifecycle with Open Formats and Interfaces. In: COMPIT '15 - 14th International Conference on Computer and IT Applications in the Maritime. Volker Bertram.

Vatteroni, M. (2016). A Standard Protocol for Exchanging Technical Data in the Maritime Industries. In: COMPIT '16 - 15th International Conference on Computer and IT Applications in the Maritime Industries. Volker Bertram.

Vaucorbeil A, Patron K. (2017) Optimization of the gun foundation structure of an offshore patrol vessel using a modern genetic algorithm, Progress in the Analysis and Design of Marine Structures, Guedes Soares & Garbatov (Eds.), Taylor & Francis Group, 2017, pp. 131-137.

Ventura M. and Soares C. Guedes. (2015) "Integration of a voyage model concept into a ship design optimization procedure". Towards Green Marine Technology and Transport (2015): 539-548

Vieira, D. P., Lavieri, R. S., Rocha, T. P., Dotta, R., Rampazzo, F. and Nishimoto, K. (2016) A Synthesis Model for FLNG Design, in. 35th International Conference on Ocean, Offshore & Arctic Engineering, Busan, South Korea: ASME, p. V001T01A015.

Vladimir, N., Senjanović, I., Malenica, Š., De Lauzon, J., Im, H., Choi, B.K. and Seung Cho, D. (2016). Structural Design Of Ultra Large Ships Based On Direct Calculation Approach. Journal of Maritime & Transportation Sciences, Volume 1, pp. 63-79

Vugts, J. H. and Zandwijk, K. van (2016) Handbook of Bottom Founded Offshore Structures. Part 2: Fixed Steel Structures. 1st Ed. Delft: Eburon.

Wagner, L., Grau, M. and Enders, O. (2015). Enterprise Architecture Management in Shipbuilding PLM. In: COMPIT '15 - 14th International Conference on Computer and IT Applications in the Maritime Industries. Volker Bertram.

Wallace, G. and Champlin, T. (2016) Online Asset Integrity Management and Operational Optimisation through Online Integrity Monitoring, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Wang, M., Wang, J., Cheng, Z., Bai, Y., Fu, D. and Luo, Y. (2017) A New Light-weight Semi-Submersible FPS for Offshore Marginal Oil and Gas Field Development, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Wiley, L. (2015) Deriving Value from Integrating Engineering Design and Automation with Offshore Operations, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Wilken, M., Cabos, C., Baumbach, D., Buder, M., Choinowski, A., Griessbach, D. and Zuev, S. (2015). IRIS – an innovative system for maritime hull structures. In: Proceedings of RINA, Royal Institution of Naval Architects - International Conference on Computer Applications in Shipbuilding 2015, ICCAS 2015. Bremen, pp. 219-226.

Wisch, D. and Spong, R. (2016) Recommended Practice for Structural Integrity Management of Floating Offshore Structures - A DeepStar 12401 Product, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Wyllie, M., Newport, A. and Mastrangelo, C. (2017) The Benefits and Limits of FPSO Standardisation, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Yan, G., Sun, H. and Waisman, H., 2015. A guided bayesian inference approach for detection of multiple flaws in structures using the extended finite element method. Computers & Structures, 152, pp.27-44.

Yang M, Khan F, Oldford D, et al. Risk-based Winterization on a North Atlantic-based Ferry Design[J]. Journal of Ship Production & Design, 2015, 31(2):1-11.

Yang, H. and Zhu, Y. (2015). Robust design optimization of supporting structure of offshore wind turbine, Journal of Marine Science and Technology, December 2015, Volume 20 (4), pp 689–702

Yang, M., Khan, F., Oldford, D. and Sulistiyono, H. (2015). Risk-based Winterization on a North Atlantic-based Ferry Design. Journal of Ship Production & Design, Volume 31 (2), pp. 1-11.

Ye, W., Ran, A., Li, J., Li, G., Tan, X., Wang, Z. and Wu, H. (2017) A Viable Dry Tree Semi-Submersible Concept with Tapered Columns, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.

Youssef, S., Kim, Y.S., Paik, J.K. and Turgut Ince, S. (2014). Quantitative risk assessment for collisions involving double hull oil tankers. Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering. Volume 156, pp. A157-A174

Yu, Q., Tan, P.-L., Lo, T.-W. and Chow, W.-Y. (2016) New LRFD-Based Design Criteria for Mobile Offshore Units and Floating Production Installations, in. Offshore Technology Conference, Houston, Texas, USA: Society of Petroleum Engineers.

Yuan, Q., Zhang, Y. and Li X.B. (2017). A new simplified method to investigate the side-by-side collision of two ships, In: Progress in the Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures (MARSTRUCT 2017). Lisbon: Taylor & Francis Group, pp. 541-547

Zagkas, V. and Spanos, G.T. (2015). An Integrated Workflow for Rapid Structural and Hydrodynamic Analysis of Ships and Offshore Structures. In: Proceedings of the 14th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT'15), Ulrichshusen, pp 563-571

Zaman, M.B., Kobayashi, E., Wakabayashi, N., Maimun, A. (2015). Development of Risk Based Collision (RBC) Model for Tanker Ship Using AIS Data in the Malacca Straits, Procedia Earth and Planetary Science. Volume 14, pp. 128-135.

Zhang, W., Cassidy, M. J. and Tian, Y. (2015) 3D Large Deformation Finite Element Analyses of Jack-up Reinstallations near Idealised Footprints, in. 15th International Conference: The Jack-Up Platform, London.

Zhang, X. Y., Li, Y. P., Yi, J. T., Lee, F. H., Tan, P. L., Wu, J. F. and Wang, S. Q. (2015) A Novel Spudcan Design for Improving Foundation Performance, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

Zhang, Y., Khoa, H. D. V., Meyer, V. and Cassidy, M. J. (2015) Jack-up Spudcan Penetration Analysis: Review of Semi-analytical and Numerical Methods, in Meyer, V. (ed.) Frontiers in offshore geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, 10-12 June 2015. Boca Raton London New York Leiden: CRC Press/Balkema.

Zhang, Y.M., Fan, M., Xiao, Z.M. and Zhang, W.G., 2016. Fatigue analysis on offshore pipelines with embedded cracks. Ocean Engineering, 117, pp.45-56.

Zou, J. (2016) Development Of Secondary Column Enhanced TLP Concept for Central Gulf Of Mexico, in Emerging offshore technology and deepwater trends: 21st Offshore Symposium 2016: Houston, Texas, USA, 16 February 2016. Red Hook, NY: SNAME/Curran Associates, Inc.

Zou, J. (2017) Conceptual Study of a Paired-Column Semi-Submersible Platform for A 1.5 MTPA FLNG, in Redefining Offshore Development: Technologies and Solutions: 22nd Offshore Symposium 2017: Houston, Texas, USA, 02 February 2017. Red Hook, NY: SNAME/Curran Associates, Inc.