AN APPROACH TO MEASURING SHIP DESIGN COMPLEXITY

(Reference No: IJME697, DOI No: 10.5750/ijme.v163iA2.763)

A Ebrahimi Ulstein International AS, Ulsteinvik and Department of Marine Technology NTNU, Trondheim, Norway and **S O Erikstad** Department of Marine Technology NTNU, Norway and **P O Brett**, Ulstein International AS, Ulsteinvik and Department of Marine Technology NTNU, Trondheim, Norway and **B E Asbjørnslett** Department of Marine Technology NTNU, Norway

KEY DATES: Submitted: 18/01/21; Final acceptance: 03/04/21; Published 12/07/21

SUMMARY

Understanding different aspects of complexity and measuring them properly are important steps of handling ship design complexity effectively. The main objective of this article is to develop a practical and comprehensive method to measure ship design complexity. In engineering design, complexity is measured today by different indexes and methods. This paper initially explores the applicability of such measures in a ship design context supported by a review of different relevant user-cases. However, it is acknowledged that most of these measurement methods focus on product-related complexity aspects and rarely address or quantify complexities generated by the design process, the organisation of the firm, or the market situation. Therefore, this paper introduces a new and comprehensive model to measure ship design complexity including all these aspects. The model quantifies ship design complexity by means of the following nine different descriptive factors: directional, spatial, decision-making, structural, behavioral, contextual, perceptual, temporal, and technological complexity.

NOMENCLATURE

Abbreviations

AHTS	*Anchor handling tug supply vessel*
CCS	*China classification society*
CGT	*Compensated gross tonnage*
DE	*Diesel-electric*
DP	*Design parameters*
DWT	*Deadweight*
ERN	*Environmental regulatory number*
FR	*Functional requirement*
GA	*General arrangement*
GCI	*General complexity index*
GT	*Gross tonnage*
I	*Information content*
LNG	*Liquified natural gas*
LWT	*Lightweight*
MGO	*Marine gas oil*
OCV	*Offshore construction vessel*
OSV	*Offshore support vessel*
PSV	*Platform supply vessel*
R	*Reangularity*
S	*Semiangularity*
SFOC	*Specific fuel oil consumption*

Symbols

A	Existing structural connections
A_{mn}	Different design vectors in design matrix row (m), column (n)
DP_m	Design parameter (m)
DRi	Design requirement (i)
F_{ij}	Complexity factor (i) for product type (j)
FR_n	Functional requirement (n)
M	Maximum possible connections
SPi	Solution performance (i)
T	Total elements
U	Unique elements
V	Multiplicity index

1. INTRODUCTION

Ship design is a specific customer-oriented and -dominated activity. Quite often, ship design is customised, adapted, and developed for a specific customer. the process of designing ship is a complex endeavour requiring the successful coordination of many disciplines, of both technical and non-technical nature, and of individual experts to arrive at valuable design solutions (Papanikolaou, 2010). Vessel size and hull shape, multitude and the diversity of equipment/systems chosen for the design and their internal interactions are important complexity drivers. In this context, multitude means the number of installed systems as an explicit complexity driver and diversity refers to their variations in type, brands, functionalities, and features. In addition to these physical items, the dynamics of the context within which the ship design organisation exists also influence the complexity. Market volatility, the variety of stakeholders, and their different expectations, the misinterpretation of customer needs, and ambiguities around new rules and regulations are also other drivers of ship design complexity.

To find an effective way of handling design complexity, measuring it, is a primary step (Suh, 2005). In engineering design literature, several measures and indexes are introduced and suggested to measure the complexity. Indexes such as Reangularity and Semiangularity (Suh, 1990); product density, redundancy, and path indexes (H. A. ElMaraghy et al., 2005); information content (Suh, 1990), and architectural temperature (Salingaros, 2014) are examples of such complexity measurement methods. Another popular index is compensated gross tonnage (CGT), which specifically addresses ship design solution complexity. Typically, these measures address one or two related aspects of complexity according to their domain of application. By conducting an extensive literature review study, we identified nine factors of a kind – directional, spatial, decision-making, structural, behavioural, contextual, perceptual, temporal, and technological – as main factors influencing ship design complexity (Table 1, F1-F9) (Ebrahimi et al., 2021). These nine factors and their related items are suggested by this paper to constitute a new and more comprehensive measurement model of ship design complexity for the future.

Table 1: The nine complexity factors adapted from (Ebrahimi et al., 2020)

	Complexity Factors	Definition	References
F1	Structural complexity	Complexity is driven by the number and variety of elements, components, interrelationships, and dynamics	(Andrews, 2018b; H. A. ElMaraghy et al., 2005; Lindemann et al., 2009; Maurer, 2017; Simon, 1973; Suh, 1990)
F2	Temporal complexity	Historical decisions and events and the presence of system dimensions over time	(ElMaraghy, 2005; Neely, 2012; Maurer, 2017)
F3	Behavioural complexity	Performance, operations, and reactions to stimuli and the interactions between the elements of the system	(Andrews, 2017; Bode & Wagner, 2015; Gaspar, Rhodes, et al., 2012; Rhodes & Ross, 2010)
F4	Spatial complexity	The network of infrastructure or customers or suppliers distributed in different spatial regions required memories for process or spaces or resources	(Alabdulkareem et al., 2007 Kolmogorov, 1998)
F5	Contextual complexity	The environment in which the system operates and corresponding uncertainties being present	(Andrews, 2018b; Gaspar, Rhodes, et al., 2012; Luzeaux, 2013; Rhodes & Ross, 2010)
F6	Perceptual complexity	Human perceptions and semantics of the design and the problem. Stakeholder preferences, perceptions, and cognitive basis	(Andrews, 2011, 2018a; Gaspar, Ross, et al., 2012; Rhodes & Ross, 2010; Suh, 2005)(Andrews, 2011)
F7	Decision-making complexity	Decision points in the design process and the diversity and influential power of different decision-makers involved in design development	(Andrews, 2018b; Budde et al., 2015; Maurer & Lindemann, 2007; Porter, 1985)
F8	Directional complexity	Unshared goals, unclear meanings, and hidden agendas – unstable organisation – ambiguous project goals	(Remington and Pollack, 2013; Azim, 2010)
F9	Technological complexity	Doing something fundamentally new where technology either has to be developed from scratch or embedding new technology in current product	(Braha & Bar-Yam, 2007; Tani & Cimatti, 2008)

This article explores the research question' *can we measure ship design complexity in the early design phase in a practical way?'*. The goal is to develop a comprehensive complexity measurement model to cover different complexity items driven from sources of product, process, organization, or market. To develop our new comprehensive measurement model, we follow three main steps. First, we review different existing measures and check their applicability and relevance to ship design. Different cases from the cruise ship sector and offshore vessels are used to verify the applicability of the measures in daily ship design practices. We have critically scrutinised which complexity factor or factors can be measured by different existing methods. As a subsequent step, we introduce and elaborate a comprehensive ship design complexity measurement model consisting of nine complexity factors. Offshore support vessels designed by eight major Norwegian ship designers are used to apply the developed complexity measurement model. The database collected and collated for this study covers 486 vessels, designed after 2000 and sold to 130 different ship owners. The vessels are built at different shipyards worldwide and represent 100 different design classes. This paper finally discusses and concludes which further relevant studies are necessary to expand this topic and utilise the findings of this study in daily ship design practice.

2. COMPLEXITY MEASUREMENT IN ENGINEERING DESIGN

2.1. COMPLEXITY MEASUREMENT METHODS

In the literature, complexity is typically modeled and measured either by information content, such as the Shannon entropy model (Kumari & Kulkarni, 2016; Suh, 2005), or by the structural complexity of the system or product (Lindemann et al., 2009; Suh, 2001). Existing methods and complexity measurement models use objective data to assess complexity (Efthymiou et al., 2016). Kolmogorov (1998) defines the level of complexity based on the number of words needed for an accurate description of a system or computational algorithm. The lower the number of lines in a software program providing similar results is an indication of lower complexity, according to him. Jacobs (2013) introduces a general complexity index (GCI) to quantify the complexity in engineering design by measuring multiplicity, diversity, and interconnectedness. Multiplicity is a representation of numbers (with or without a difference) of components, modules, features, products, suppliers, etc. Diversity captures the degree of dissimilarity among the components (Equation 1). The other element in Jacobs's (2013) index is the degree of interconnectivity. Product structure diagrams with fewer connections, such as those with lower total density compared with theoretically possible density, are less complex. He measures interconnectedness, as in (Equation 2). The product of the three measures is introduced by Jacobs (2013) as a GCI to quantify the total complexity (Equation 3). The multitude, diversity, and interconnectivity of elements are also used to quantify complexity in the product portfolio, logistics, and design development (Backlund, 2002; Becz et al., 2010; Hornby, 2007; Schuh, 2016)

$\text{Multiplicity} = \text{number of variants} = V$

$\text{Diversity} = 1 - (\text{unique elements/total elements}) = 1 - \frac{U}{T}$ (Equation 2)

$\text{Interconnectedness} = \frac{\text{Connection}}{\text{max connextion}} = \frac{A}{M}$ (Equation 2)

$\text{GCI} = \text{Multiplicity} * \text{Diversity} * \text{Interconnectedness}$

$$GCI = V * \left(1 - \frac{U}{T}\right) * A/M \quad \text{(Equation 3)}$$

Figure 1 compares the complexity in the automobile, aircraft, and shipbuilding industries according to such a measurement model. The normalised complexity score is calculated based on the multiplicity of elements, the total required time to produce, and the total line to explain the object and weight of the product (Equation 5), where F_i represents the four measurement factors, and (j) is the number of products in the sample. The figure shows how complexity increases substantially moving towards, for example, large cruise ships.

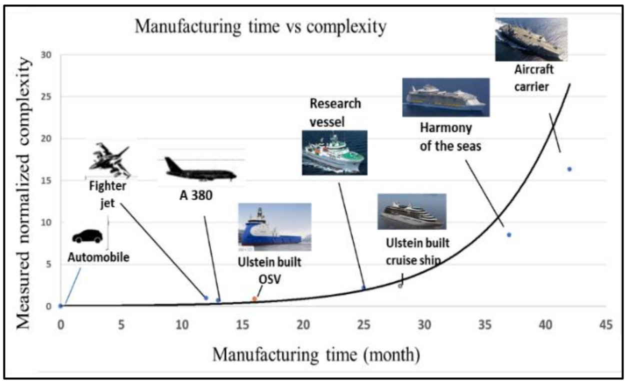


Figure 1: Complexity comparison between ships and other products, adapted from (CESA EU, 2018)

$$\sum_{i=1}^{4} \sum_{j=1}^{8} \frac{F_{ij}}{Aerage\ F_i} \quad \text{(Equation 5)}$$

As illustrated in Figure 1, based on gathered data to manufacture a car, the total number of hours used is only 23 hours for 3000 assembly parts and 1,9 tonnes of weights with the overall measured complexity of 0,01. These numbers are increasing substantially in the shipbuilding industry. For a research vessel, almost 1 million hours are needed for its construction. The number of parts increases to 550 000 and the weight to 3000 tonnes, respectively, representing a complexity score of 2,5 with almost 25 months of production time. Vessel parts include all system and subsystem elements like girders, stiffeners, plates, equipment, sensors, pipes for different systems, and cables. Exponential growth in the consumed manufacturing time and the number of parts involved is the consequence, approaching the most complex segments of large aircraft carriers and mega cruise vessels.

Nikos (2014) measures the extent of organised or disorganised complexity by two indexes of 'architectural temperature' and 'architectural harmony'. The first index of the method counts the number of pieces of raw information content, internal differentiation, and number and variety of components and contrasting elements as a measure to quantify the complexity. He calls this measure 'architectural temperature' (Nikos, 2014). This index is fairly compatible with the GCI of Jacobs (2013). In the second index, he quantifies the organising mechanisms of a complex system by the number of symmetries, scaled elements, and connections of all types. He argues that systems or structures with a wider range of element scales are more complex than systems with a lower degree of scale variety.

Wu et al. (2016) address the visual complexity for a similar purpose and use this type of complexity to measure its influence on the perception of the customers. They argue the willingness-to-purchase of buyers is positively influenced if the buyers perceive the information pieces shown in a product picture as easy to identify and understand. The general arrangement (GA) and an outline specification of a vessel are some of the more important contractual documents in a ship design setting. These documents are typically provided in the early phases of the ship design process to convey important information about the final product to the customer. The type of information and the degree of details included in these documents is a matter of cost, time, and in some cases the requirements of the customer.

Figure 2a) and Figure 2b) compare two GAs for a cruise ship with different level of details. The level of detail provided in Figure 2a represents almost 20 times higher visual complexity based on the variety of elements, scale diversity, and level of detail of material types in contrast to Figure 2b. For example, in Figure 2a, all furniture, scape ways, doors, windows, ladder, stairs, and safety signs are detailed with their material type. While figure 2b mainly demonstrates the functional areas and required compartments.

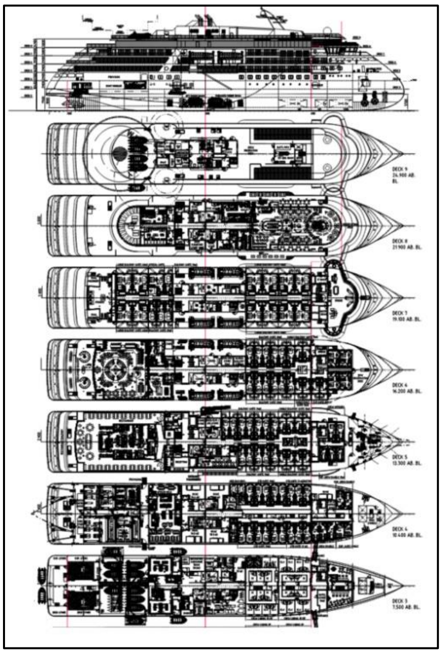


Figure 2: a) Detailed cruise ship GA

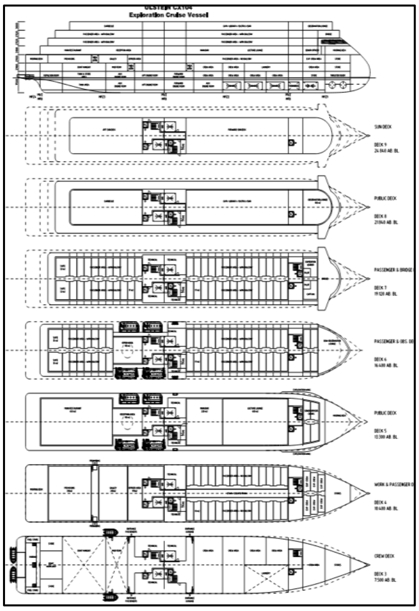


Figure 2 b) Less detailed GA

The result of studies from the visual complexity literature (Oliva et al., 2004) and our experiences at Ulstein correspond well with each other. Based on our experiences, providing more detailed information in the GA and/or outline specification of the ship design solution may lead to ineffective communication and information sharing in the early design phase. In addition to levels of visual detail and scale diversity in the design, the variety of languages, cultures, flag rules and regulations, experiences and domain knowledge among different customers, also increase the complexity (Azim, 2010; San Cristóbal et al., 2018). Design firms selling designs to different countries and a wide range of customers, typically, face higher complexity than those operating in a narrow local market, where the expectations of the customers are well interpreted.

Suh (2001) introduces two terminologies/measures of Reangularity (R) and Semiangularity (S) to determine the level of structural/architectural complexity in design. Interdependency between functional requirements and the cross-correlation between functional requirements and design parameters are measured by these indexes. Reangularity (R) is a value that has an inverse relationship to coupling and measures the orthogonality between design parameters. If R is 0, the design is completely coupled (Equation 6). Semiangularity (S) characterises the functional independence between design parameters and functional requirements (Equation 7). Semangularity is a value that, when equal to unity, 1, then the design is uncoupled providing the Reangularity is also equal to unity, 1. In equations 6 and 7, A_{mn} represents different vectors of the design matrix. These vectors connect functional requirements (FRs) to design parameters (DPs) (Equation 8).

$$R = \prod_{\substack{i=1,n-1 \\ J=i+1,n}} \left(\mathbf{1} - \frac{\left(\sum_{k=1}^{n} A_{ki} A_{kj}\right)^{2}}{\left(\left(\sum_{k=1}^{n} A_{k_i}^{2}\right) * \left(\sum_{k=1}^{n} A_{k_j}^{2}\right)\right)} \right)^{\mathbf{0.5}} \quad \text{(Equation 6)}$$

$$S = \prod_{j=1}^{n} \left(\frac{|A_{ij}|}{\left(\sum_{k=1}^{n} A_{kj}^{2}\right)^{0.5}} \right) \quad \text{(Equation 7)}$$

$$\begin{Bmatrix} FR1 \\ FR2 \\ . \\ FRn \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & . \\ A_{21} & A_{22} & A_{23} & . \\ . & . & . & . \\ . & . & . & A_{mn} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ . \\ DP_m \end{bmatrix} \quad \text{(Equation 8)}$$

Another supplementary study by the authors of this article has examined the applicability of these indexes in ship design by measuring the complexity of a simple deck barge (Appendix A). The result of that study shows that developing such advanced mathematics in the design matrixes for more complex ships is at least an extremely time-consuming task if not impossible. Hence the method is difficult to apply in a real design practice situation. Based on the finding of that study we could argue that developing a design structure matrix can be used as a simpler indication to compare the system architecture related structural complexities of different design solutions. The tally count of interconnections among functional requirements and design parameters, which are defined by binary values of 1 and 0 in the matrix, indicates higher level of complexity in design.

Information content (I), or Shannon entropy, is another index that measures the functional performance/ behavioural complexity of a ship design. The measure is used to rank and select among different design alternatives due to their probability of satisfying functional requirements (Tauhid, 2007; Vinodh, 2015). This index is a measure of the probability of the success of achieving the initial functional requirement (Equation 9a). Where the probability of satisfying the functional requirement is higher, the information content is lower (Suh, 2001; Elmaraghy et al., 2012; Kulak, 2005; Braha and Bar-Yam, 2007; Levin et al., 2007; Mocko and Porter, 2008). If the information content is considered in terms of accuracy (or tolerance), the design range is defined as the tolerance associated with design parameters specified by the naval architect. In this context, the system range is the capability of the manufacturing system given in terms of tolerances (Equation 9b).

$$\text{a) } I = log_2\left(\frac{1}{P}\right) \qquad \text{b) } I = log_2\left(\frac{System\ Range}{Common\ range}\right)$$

(Equation 9)

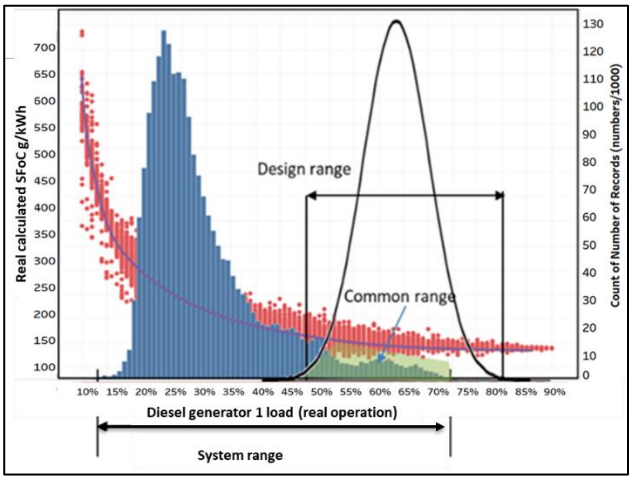


Figure 3: System range and design range applied on real fuel consumption data from a service offshore vessel

This method was applied to retrieved data from a six-month operation of a service offshore vessel (SOV). The result shows that all four engines are operated at almost 80% of their operation time, in the ranges between 15% - 40% of their maximum nominal power rating. Real engine specific fuel oil consumption (SFOC) is between two to three times higher than the optimum SFOC in those loads according to our calculations. Theoretically, medium size marine diesel engines consume 200–220 g/kW.hr (gram/kilowatt-hour) as optimum SFOC at loads of 80–90% of nominal max power rating. The blue bars in Figure 3 show the load distribution of one engine (system range), and the red dots present its real SFOC during operation. The black normal distribution shows the design range, which is the desired performance frequency distribution curve. The common range is shown as the green area between the design range and the system range in Figure 4. By applying (Equation 7b), the information content for the design is calculated as 1,6. The common range is improved by altering the engine room configuration and adding a 1-MWh (megawatt-hour) battery pack to the system. The value of information content (I) is reduced to 0,3 in the new design solution, which indicates lower behavioural complexity compared to the original design. However, moving towards such a hybrid solution requires more system elements and extra interconnectedness, which means higher system architecture structural complexity in the design.

The other method, which assesses the structural complexity of the manufacturing system layout or process, is introduced and applied by ElMaraghy et al. (2005) and Lindemann et al. (2009). The method is developed based on graph theory and includes six static measures, (ElMaraghy et al., 2005). These six complexity indices are defined as follows: density index: number of connections between the nodes; path index: number of paths; cycle index: number of cycles in the graph; decision points index: the sum of all nodes between input and output; redundancy distribution index: number of occurrences of redundancy between adjacent nodes; and redundancy magnitude index: number of redundant parallel arrows in the system layout. Technology advancement is another source of complexity, which is addressed and measured by the number of registered patents in different technological aspects (Broekel, 2017). Three indexes of reflective technology measure, knowledge combination measure, and structural complexity of technologies are used in the literature for technological complexity measurement (Broekel, 2017).

Other more simplistic methods in the literature suggest to measure the complexity based on the geographical distribution of the design or production facilities (Kohr et al., 2017), a number of hours or resources that are used to run the analysis (Liao, 2016), and the number of internal or external entities involved in the process (Howard and Rolland, 2004), which are used in the developed ship design complexity measurement model of this article.

2.2. COMPLEXITY MEASUREMENT IN THE SHIP DESIGN LITERATURE

As an alternative to information content (I), focusing on ship design problems, Ulstein company has developed and implemented a Goodness of Fit (GOOF) index for the same purpose over the years (Brett et al., 2006; Ulstein & Brett, 2012). The index is developed to measure the fit of the design solution with predefined stakeholders' expectations and corresponding design parameters, (Ulstein & Brett, 2012). Several design concepts are evaluated against each other and ranked based on the GOOF index (Equation 10). Ebrahimi and Brett (2018) apply the GOOF index in the conceptual design development of cruise exploration vessels for ranking among the solutions in the following way:

$$\text{GOOF Index} = \sum_{i=1}^{n}\left(\frac{\boldsymbol{SPi\ (solution\ performance\ range)}}{\boldsymbol{DRi(design\ required\ range\ )}}\right)$$

(Equation 10)

Caprace and Rigo (2012) introduce another complexity metric for passenger ships taking into account the shape complexity of steel parts, the assembly complexity, and the material complexity. They use the sphericity ψ index, the ratio of the lateral surface of a sphere (with the same volume as the given solid) to the surface area of a 3D solid, to measure shape complexity of the ship hull. To measure the assembly complexity, they compare the hierarchical structure of the product, systems, and subsystems and argue that the higher the number of sub-structures and subsystems, the more complex the assembly process is. For material complexity, they consider only different combinations of plate thickness, profile scantling, material types, and profile types in their model. The method as presented addresses the design architecture and attempts to compare the complexity of different solutions by different structural properties. Huijgens, (2016) has introduced a method to quantify complexity in ship building projects based on the level of interdependency among vessel different systems and technological differentiation among those systems. In this model interdependency factor quantifies influence on a certain component dimension by other components and systems, while the differentiation factor quantifies mainly spatial limitations imposed on the components.

Compensated gross tonnage (CGT) is another frequently used index in ship design and shipbuilding to compare the complexity of different vessel types. The concept was originally proposed by the shipbuilder associations and later adopted by the Organisation for Economic Co-operation and Development (OECD, 2007). In contrast to produced annual gross tonnage (GT) or deadweight tonnage (DWT), the objective with CGT was to provide a more accurate measure of shipbuilding activity and workload by considering the complexity of the design and construction work. The measure is supposed to be valid and applicable at different shipyards around the world, for different ship types and sizes. CGT was initially calculated by collecting the amount of the necessary workload to build a single gross ton of different ship types and ship sizes and correlating them by a compensation factor. However, it has been admitted that different yard facilities and approaches to building ships, as well as discrepancies in offshoring and outsourcing strategies among shipyards, have a major effect on the total used man-hours and accuracy of the developed CGT factors (OECD, 2007). (Equation 11) presents the CGT formulation for different ship types, where A and B are captured from Table 2. To examine the validity of CGT for this study, the total construction hour and CGT of Ulstein-built vessels since 2000 are used for reference. Figure 4 shows the scatter diagram of CGT of different built vessels with total used manhours. Due to the confidentiality of data, manhours are divided to the average and normalized. A strong correlation of 92% was achieved, and the validity of the index is also confirmed in this study by a P value smaller than 0.0001.

$$CGT = A * GT^{B} \quad \text{(Equation 11)}$$

Table 2: CGT calculation A and B factors (OECD, 2007)

Ship type	A	B
General cargo ships	27	0,64
Reefers	27	0,68
Full container ship	19	0,68
RoRO vessel	32	0,63
Car carrier	15	0,7
Ferries	20	0,71
Passenger ships	49	0,67
Fishing vessels	24	0,71
Non cargo carrying vessels (NCCV)	46	0,62
Offshore vessels	38	0,37

Table 2 shows that the existing CGT model does not differentiate between the different offshore vessel subtypes. Therefore, a wider data span from the trend line is observed among anchor handling tug supply (AHTS) vessels, platform supply vessels (PSV), and offshore construction vessels (OCV). Hence, we conducted separate regression analyses between produced GT and total used construction man-hours of different offshore vessel subtypes. The A and B factors for the CGT calculation of AHTS, PSV, and OCV are determined as in Table 3. In this paper, corrected factors are used in the developed complexity measurement model. These factors can also be used as a basis for other practitioners to estimate the CGT of relevant offshore vessel subtypes in other settings. It is even suggested that these correction factors could be added by OECD eventually.

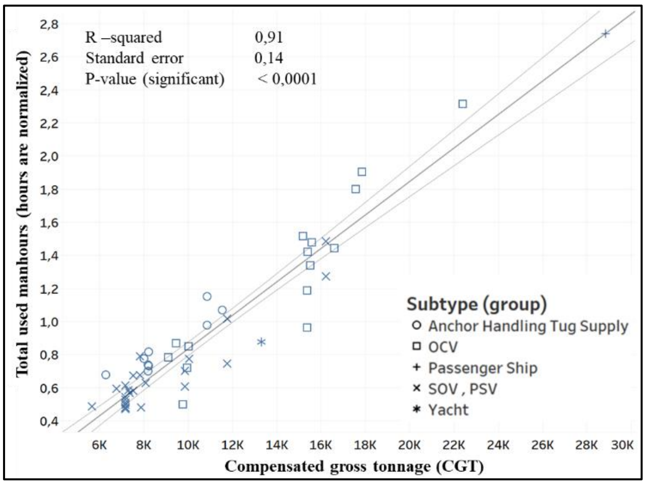


Figure 4: CGT vs total normalized man-hour Ulstein-built vessels

Table 3: A and B factors for different offshore vessel subtypes

Sub type	A	B
PSV	903	0,68
AHTS	2200	0,6
OCV	143	0,9

Diverse measures used in different industries to quantify the complexity of ship design have been briefly covered in this section of the article. Different measures to quantify product or process structural complexity were elaborated in detail. Furthermore, the other indexes quantifying the information content of the design, visual-perceptional complexity, technological complexity, spatial complexity, or shape complexity were explained and contrasted with the support of some design case-examples. The popular complexity measurement methods in ship design, including the CGT and its validity and relevance with regards to this research study were also reviewed. The summary of these methods and their connection to the nine complexity factors are presented in Figure 5. The figure shows how different identified complexity measures relating to and loading on the nine proposed complexity factors. In the next step of this research, these measures are primarily adjusted by ship design-related complexity items. For those factors for which we could not find an appropriate measure in the literature, a relevant index based on the constituting items has been introduced. The method is explained more in detail in the section 3 of this article.

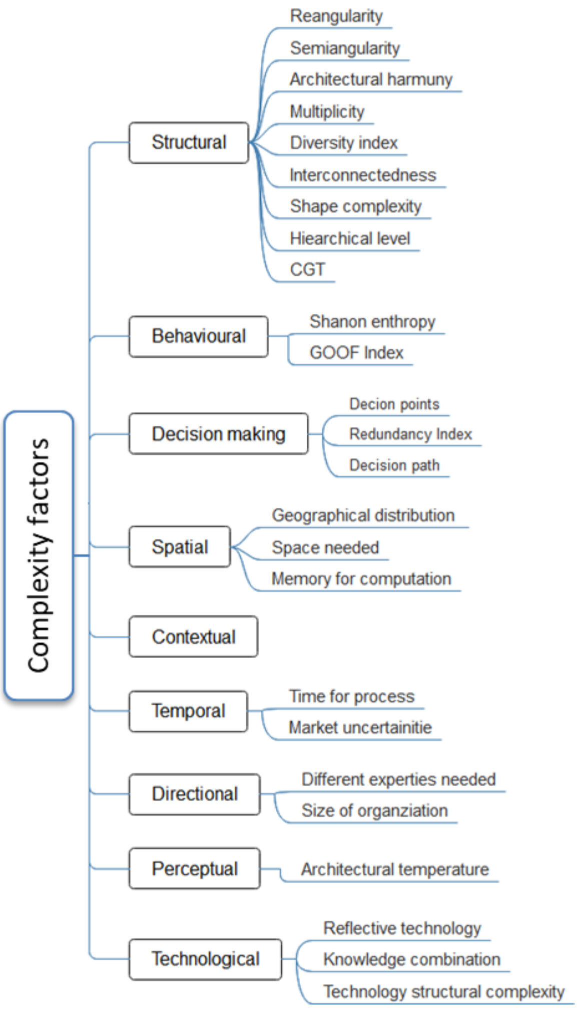


Figure 5: Complexity measures identified in the literature and their relevance to nine factors

3. A NEW AND MORE COMPREHENSIVE COMPLEXITY MEASUREMENT MODEL

To develop our complexity measurement model, the following steps were followed. First for each complexity factor explained in Table 1, four to five constituting items were identified through literature and expert suggestions. Then the nine complexity factors and their constituting items were categorized based on reviewed literature and expert judgment. An expert group in Ulstein with the participation of three experts verified the item categorisation in a supervised approach. During the expert group analysis, items were also converted to relevant and measurable items in the ship design context. Supplementary factorial analysis is also conducted to verify the result of expert judgment.

In the third step, the complexity value of each item is measured, based on the collected data. Real measured values are converted to 1 and 5 Likert scale based on their distribution as a subsequent step. In this study, a quantile classification and standard deviation methods (Ştefan, 2012) are used to convert the calculated values into a scale score of 1–5 for different complexity items of each design. Each complexity factor is calculated as a sum of its relating items (Equation 10). The internal consistency of the items inside each factor is tested out and validated by Cronbach's alpha measure (Hair et al., 2010) for the collected database.

$$Complexity\ factor\ i\ = \sum_{j=1}^{n} Related\ complexity\ items \qquad \text{(Equation 10)}$$

Figure 6 presents the results of such an item categorisation. Relevant measures to quantify the items are also demonstrated in Figure 6 in front of each item. Examples of how different complexity items and corresponding factors are measured in the newly developed comprehensive complexity measurement model are shown in the following sub-sections of this section. The real vessel and organisation data from offshore vessels and design firms are used for this complexity measurement. The next paragraphs explain the statistical characteristics of the data used in this article for such complexity measurement.

3.1. STATISTICAL CHARACTERISTICS OF COLLECTED DATA

Different offshore vessel types larger than 2000 tonnes DWT, designed after the year 2000 were selected for this complexity measurement analysis. The vessels collected in the data based were designed by eight Norwegian designers, including Ulstein (Design firm C) and sold to 130 different customers. The database for analysis includes 486 offshore vessels representing 100 vessel designs. Among the different vessel types in the sample, 48% are PSV, 26% are AHTS, and the remaining 26% are different offshore construction vessel types.
Figure 7 presents the number of offshore vessels designed by each design firm with subtype categorization. As presented, Design firms A and B have the highest share in the database, with 120 and 108 vessels in the market. Design firm C, with 73 offshore vessels, stands behind the first two design firms. Other design firms maintain the next positions in the database, respectively.

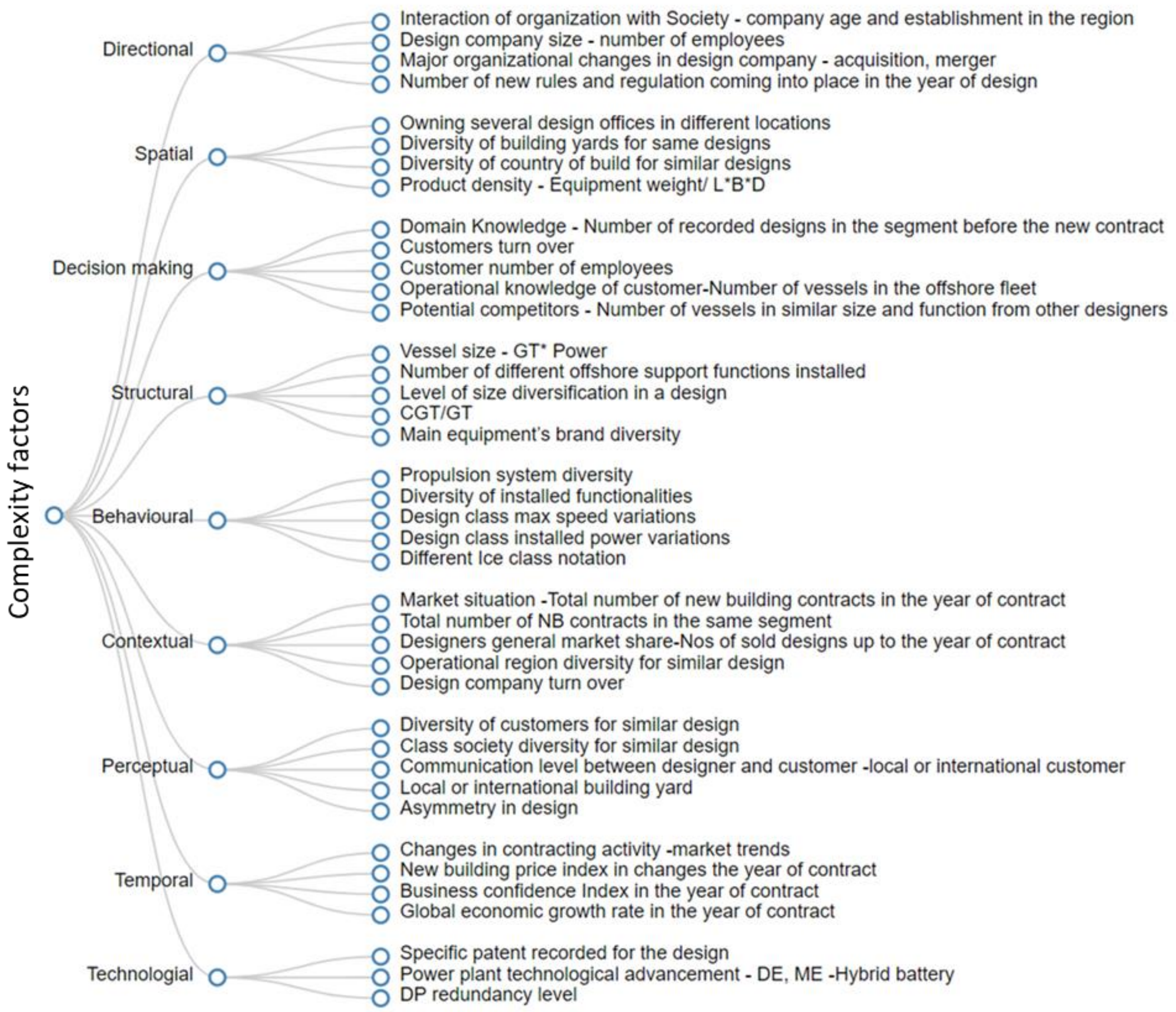


Figure 6: Complexity factors and items identified relating to ship design

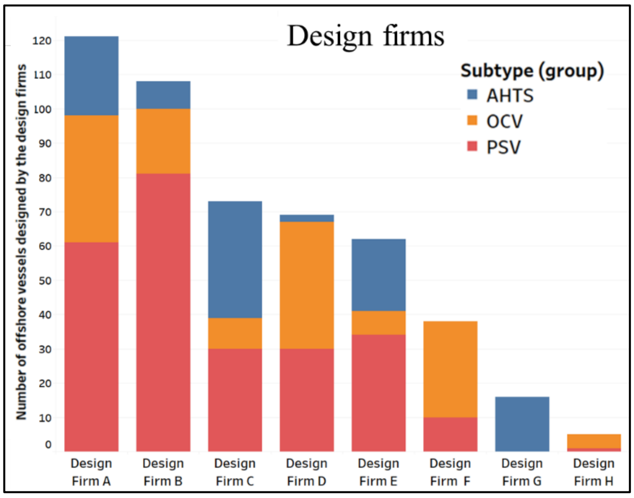


Figure 7: Vessels, designed by each design firm in the database

For the selection of the sample data, the registered vessel information available in the 'World Register of Ships' (IHS Fairplay, Q1, 2020, and Q4, 2015) (Ulstein vessel segment database, 2020) as well as enterprise information webpages, including Proff.no (2020), Bloomberg (2020), and LinkedIn (2020), have been used. Other relevant supplementary public information, available on the Internet, about different vessel particulars and websites of different ship design and ship owning companies, are also used in the data collection process.

3.2. MEASURING SHIP DESIGN COMPLEXITY BY THE COMPREHENSIVE COMPLEXITY MEASUREMENT MODEL

In the following paragraphs of this article, complexity of different ship designs are measured based on nine different complexity factors and their related items, reflecting the product, the process, and the firm/ organisation behind it.

A brief explanation of each factor and the way the items are calculated are presented in this sub-section of the paper. A more detailed calculation of items and factors are provided in Appendix B.

Directional complexity: very often is characterised by unshared goals and objectives, which are overshadowed by unclear meanings and hidden agendas. Based on the reviewed literature, four items, including interaction of organisation and society, design company size, major organisational changes over time, and changes in rules and regulations, are selected to measure this type of complexity. Ihlen and Verhoeven (2017) argue that company culture and communication links with society have consequences on how organisations construct their identity to define goals and objectives. To measure such a communication, the age and the level of the establishment of the design company (Turyakira et al., 2014) in the year of the design contract is used. The year for the first design contract is used as a reference for those design solutions which are contracted several times over the study period. Typically, there is a weaker societal establishment for younger and immature design organisations/firms. Figure 8 shows the age distribution of the design companies in the year of the design contract. Design company size is measured by the number of employees in the year of the contract. The larger the size of the company, the effectiveness of communicating organizational goals and objectives to the employees can be lower (Amah et al., 2013). This type of complexity is experienced in our daily design work at Ulstein. Typically, when the number of participants in meetings exceeds a certain size of 5 participants, the effectiveness of the meetings reduces dramatically. It is extremely difficult to achieve a common understanding of the problem at hand in such circumstances. Unstable organisations are challenged with higher directional complexity. The number of changes in the top-level management or board members as well as mergers or acquisitions are counted and scored between 1 and 5 for different design companies to measure this item.

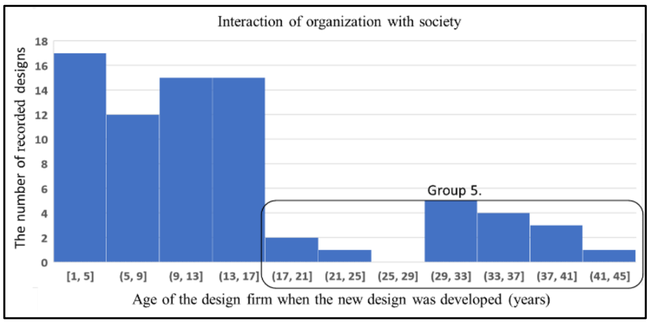


Figure 8: Age distribution of design firms in the design time

Spatial complexity: this type of complexity relates to the geographical distribution of suppliers, shipyards involved to build a design or distribution of the design team. Based on our reviewed literature three complexity items/drivers increase spatial complexity of the design process. These items include 1): A design firm owns and runs several design offices in different geographical areas, 2) a design firm builds one design in different shipyards of one country 3) or similar design is built in different countries for different customers. At the product level, two ships with similar installed functions can have different compartmentation and internal arrangements. Typically, to design a vessel with a higher number of equipment to be arranged in more confined spaces, requires more time and considerations. In this article such space-related complexity issues in the design is explained as part of spatial complexity. To measure this item, the ratio of the minimum required space for vessel systems to the total provided volume in the main hull is suggested. The higher the ratio indicates higher product-related spatial complexity. Vessel lightweight divided by the cubic volume of the vessel is used for this measurement.

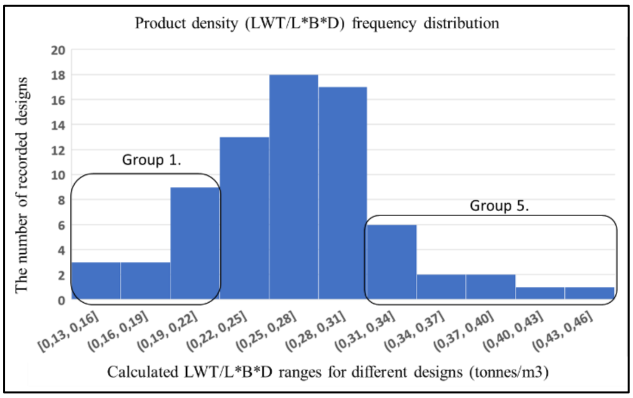


Figure 9: Distribution of equipment weight /L*B*D ratio

As Figure 9 shows, the ratios are almost normally distributed. By using quantile categorisation, the first three ratio intervals are accumulated together in group 1. This group has the lowest equipment weight /L*B*D ratio among the categories and therefore scores 1 for this item of spatial complexity. The last four size intervals are grouped as group 5 with the highest complexity score of 5. The three middle groups are scored 2 to 4 respectively. Each group in the categorization represents complexity Likert scales.

Decision-making complexity: to measure the decision-making complexity, the domain knowledge of the ship designers, the influencing power of the customers, and substitute solutions are the constituting items. The domain knowledge of design firm and designers is measured through the number of designs developed by the designer in the same segment in the years prior to the new design contract. Such domain knowledge helps the designer to effectively reduce the number of possible solutions concerning the main dimensions, equipment choices, and installed functionality. The power of the customers is reflected by turnover, size, and domain knowledge. The number of similar-type vessels in the customer's operating fleet indicates their domain knowledge in the segment. These data are gathered for the original customers of each different built vessel and categorised in a 1 to 5 scoring system. To measure the substitute design, the potential designs from competitors are counted. By potential design solutions, vessels in the same segment with similar functionality and comparable capacity and capability ranges is meant. For instance, in the year of the first contract for a design (C008, 2012), 38 PSV designs in the size range of 3850

DWT–4150 DWT, designed and built by competitors of Designer C, were in operation in the market. Each of those designs could have been considered as a substitute product by the customer. The higher the number of substitute products for each design reflects higher decision-making complexity.

Structural complexity: to quantify the structural complexity of the system architecture in this study, vessel size, number of installed offshore functions, size diversity, volumetric complexity, and brand choice diversity are measured for each design solution. Vessel size is measured by a product of GT and installed power, where GT reflects the vessel's main dimensions and accommodation size, and installed power indicates the size and quantity of the main machinery and propulsion system. The other measuring item for the structural complexity factor is the size diversification of a design solution. This item measures the variations in the main dimensions of a specific design solution and demonstrates the variety inside each product class. For example, design class B001, which is categorised as a diving vessel, is sold 12 times between the years 2010 and 2014. Among the sold vessels with the same design name, 30% variation in vessel beam (between 25m and 30m), 10% variation in the design draft (between 7m and 7,7m), 2,5% variation in length (between 125,4m and 128,5m), and 38% variation in vessel DWT (between 7000 and 9680 tonnes) is observed. Such size variations inside each design class, especially in the beam of the vessel, drive extra design analysis work and requires more resources to provide the necessary changes and adjustments. To reflect the complexities due to the compactness of architecture, the volumetric complexity ratio is used. The volumetric complexity is measured by the ratio of CGT to GT of each design. This ratio is higher for smaller and more equipped vessels, such as AHTS, compared to larger offshore service vessels. Figure 10 presents the distribution of volumetric complexity among the different design solutions of our sample data.

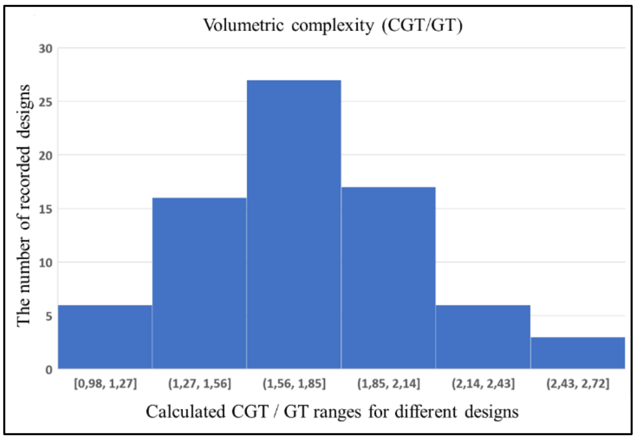


Figure 10: Volumetric CGT distribution of different design solutions

Behavioural complexity: behavioural complexity reflects performance variances in response to external intensive like environmental conditions or unpredictable behavior of the vessel in different operational mode. According to literature uncertainties around satisfying, functional requirements increases behavioural complexity. To quantify this type of complexity, functional diversities inside each design class are suggested and used as measurement criteria. Different types of the installed power plant and propulsion system, variations in installed functionalities, different design speeds, and ice-class capability alterations inside each design class are counted to quantify functional complexity of each design. In this study, behavioural complexity, distinguishes between variants of a design class, and quantifies design complexity when required functionality changes from one customer to another. For example, the design class of D002 (Ulstein, 2020) is sold five times over the years to three different customers. Three different functionalities of offshore survey and maintenance, offshore supply, and pipelaying are installed in different vessels under the same design class. Such functional diversity depicts the flexibility of the designer to provide different functions under the same design class. However, such changes might have consequences related to vessel size, speed, accommodation size, or installed power and vessel overall performance in different operational modes. Diversity in ice strengthening is another item that directly influences system behaviour in the operation. This item influences the hull weight, propeller size and efficiency, and alloys used to manufacture the propeller as well as machinery and system costs. Other design aspects, such as vessel stability and cargo-carrying capability, are also influenced by changing ice strengthening of a design solution.

Contextual complexity: reflects the environment in which a design is developed, or a system operates or is designed for. This type of complexity is addressed by items covering the market situation, operational environment, and organisational status during design development. The total number of new building contracts addresses the market situation in the year of the design contract (Figure 11).

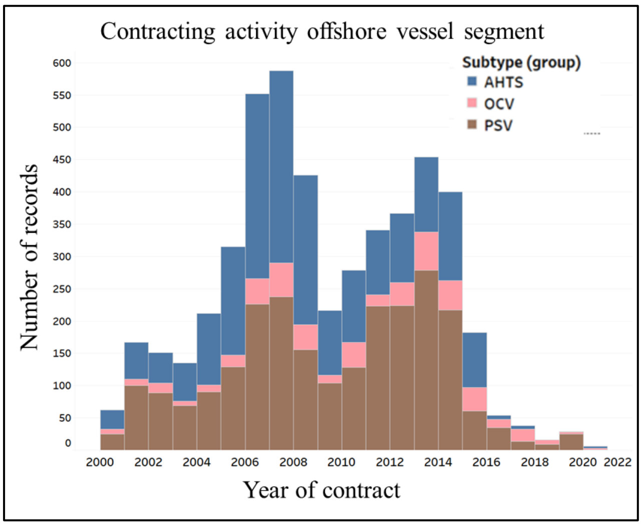


Figure 11: The total number of registered new building contracts, different offshore vessel segments (IHS Fairplay, 2020, Q1)

Based on available experiences at Ulstein, it is suggested that in years with a higher number of global OSV contracts, design companies faced fewer difficulties to introduce new designs to the market, compared to bad market conditions. Hence those designs being sold in bad market conditions are scored higher in this complexity item. The designer's general market share and the turnover of the design company in the contract year address the reputation and experience of the designer in the market segment. Higher market reputation and better financial status of a design firm proportionally enhance the chances to win a contract. A lower reputation in the segment requires more resources for entering the market and finding relevant customers. The total number of sold designs in the relevant segment up to the year of the contract is used as an indication of market share. And eventually, the environmental regularity (ERN) number and vessel operating region are used to quantify the associated complexity due to the operational environment. Designing for different operational environments has implications and consequences regarding design specification, which requires more evaluation and exploring different alternative solutions.

Perceptual complexity - cross cultural: in the developed measurement method perceptual complexity is quantified through items that reflect the communication issues between the designers and external stakeholders involved in the design. The country of build, diversity of class society, variety of customers, and nationality of customer/s have been counted and categorised for measurement of this factor. For example, design D006 is sold six times to three different customers, where the customers have been both Norwegian and international. Three different shipyards from three different countries, including Norway, and two different class societies have been used to build these six vessels. Experiences at Ulstein and discussions with experts support the premise that building in a Norwegian shipyard is typically less resource-demanding for Norwegian designers in terms of conveying the right information to the yard and achieving a common understanding of the level of detailing in the drawings than building in foreign-based yards. The definitions of the type and the details included in the deliverables covered in the conceptual design, basic design, and detailed design vary substantially from one yard to another and from one country to another. Based on available practices, more detailed drawings are needed with clear text and without any single fail when the design is going to be built in, for example, East Asia compared to Norway.

Temporal complexity – market economic complexity: temporal complexity presents the system dimensions over time. To measure the temporal complexity four items of changes in contracting activity, offshore vessel fleet growth, global economic growth rate in the contract year, business confidence index, and new building price index are used. All these items depict the market situation and available risks and uncertainties over time for new building investments due to the stability or volatility of the market. Designs that are contracted in less volatile years are exposed to less temporal complexity compared to those contracts which are signed during significant fluctuations. Although global growth has been varying between -2% to 5% over the studied years, much larger fluctuations in shipbuilding contracting activity and changes in the new building index are noticed in these years (Figure 12).

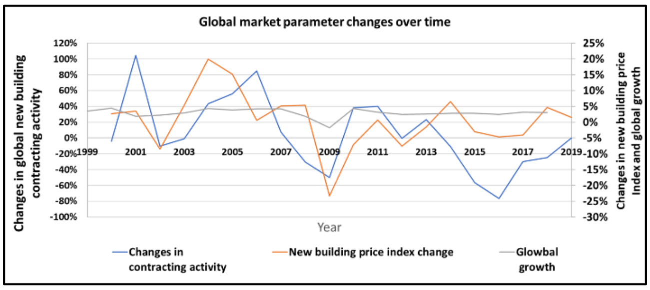


Figure 12: Global shipbuilding and market economy indexes

Technological complexity: to measure technological complexity, the registered number of patents for different designs, implemented new technologies in machinery systems or any technological advancements which are recorded for different designs over the year are counted and used as a complexity measure.

4. FURTHER EXPLANATION ON THE UTILITY OF THE METHOD – USER CASES

By applying the explained complexity measurement approach on gathered offshore vessel data, we quantified the level of complexity for each complexity factor as a total sum of its items. Figure 13 shows the distribution of structural complexity for all 100 design solutions database. Scores are normally distributed between 3 and 20, where the higher frequency of designs are scored between 13 and 15. In terms of structural complexity, the results show that AHTS vessels are typically more complex in structural complexity than the other subtypes because of high installed power, a relatively higher CGT/GT ratio, and the number of systems installed onboard. Among the OCVs, typically, diving vessels or pipelayers are more structurally complex than IMR (inspection, maintenance, and repair) vessels or crane vessels.

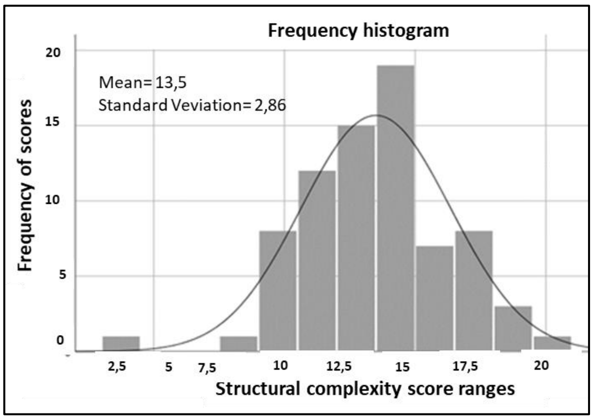


Figure 13: Structural complexity frequency distribution

4.1. USER CASE 1: MEASURING AND COMPARING THE COMPLEXITY OF SOME OFFSHORE VESSELS

As explained in the previous chapter complexity factors were calculated for all 100 vessels in the database, based on the developed measurement approach. For this case seven different designs were chosen randomly from the database to examine and evaluate the performance of measures. The vessel type, size, year of contract, and score for different complexity factors of the solutions are listed in Table 4. The selected sample consists of four construction vessels, one AHTS, and two PSV's. All complexity scores are standardized and made dimensionless. Complexity numbers are calculated based on procedure explained in the Appendix B of this article.

Table 4: Standardized scores of different complexity factors

Design name	Design development year	Subtype	Vessel Loa (m)	Directional complexity	Spatial complexity	Decision making complexity	Structural complexity	Behavioural complexity	Contextual complexity	Perceptual complexity	Temporal complexity	Technological complexity
A 01	2005	OCV	105,9	10	8,75	12	12,25	7	16	5,3	8	8,3
B 01	2015	OCV	98,1	15	10	15	11,25	7	13	5,3	14	10
G 01	2011	OCV	160,9	8	5,25	23	14,25	7	20	8,7	16	10
B 02	2013	OCV	145,4	13	10	14	13,25	8	14	5,3	10	11,7
C 01	2005	AHTS	86,2	13	10,5	12	16,75	15	18	15,3	14	10
E 01	2006	PSV	93,6	14	15,5	12	16	11	14	6,3	8	8,3
C 02	2010	PSV	83,4	12	6,5	10	9,25	7	20	6,3	11	8,3

The results show that the B01 vessel design has the highest score in directional complexity. This observation means that at the time of developing this design solution, the ship designers at design company B experienced a less transparent and less stable situation compared to other design firms. Among the selected cases, the highest spatial complexity score is given to design E01. This score is the result of a combination of product-, process-, and organization-oriented influences. The design is a PSV with a crane and winches for utility support function. It has been sold 14 times, while Design firm E at the time of developing this design owned three different design offices globally. The design was built at five different shipyards in three different countries. The reason for such a high spatial complexity for this design relates to the geographical distribution of the design offices, suppliers, building yards, and countries of the build. However, the flexibility of Design firm E to deal with such extra complexity has increased the market success of this design solution substantially.

The design G01 was developed while Design firm G had low experience in the construction vessel segment and several other competing designs with similar functionalities existing in the market. Therefore, the decision-making complexity for this vessel design has been calculated to be higher than other peer vessels in the sample. This design is also scored higher in the temporal complexity factor because of high market fluctuations in the year of development. The highest score of structural, functional, and perceptual complexity among these selected designs has been calculated for design C01. The design is an AHTS vessel with a hybrid diesel-electric power plant. The advanced hybrid power-plant configuration of this design increased its structural and behavioural complexity. The design has been sold to a diverse range of customers under different class societies' rules and is built in different countries. Vessel design C02 and G01 obtained the highest contextual complexity scores. Both designs were developed for harsh environmental conditions. Moreover, the market situation and the financial statuses of the design firms in the year of developing these designs were relatively weak compared to competing design firms. The technological complexity does not show a considerable difference between the selected solutions. The reason for such a narrow span is the similarity of the technological levels used among different offshore vessels between different Norwegian design firms. However, concepts such as X-Bow, X-Stern, or alternative fuels such as LNG in some of the designs represent higher technological complexity compared to more conventional design solutions.

4.2. USER CASE 2: APPLYING THE METHOD FOR DESIGN PROJECT PRIORITIZATION

Developed complexity measurement model can also be used in the upstream business case evaluation for ship design project prioritization decisions. In this case, design firm X from Norway, needs to select between two design projects P1 and P2 with the following project criteria (Table 5).

Table 5: Standardized scores of different complexity factors

Project criteria	P1	P2
Vessel type	AHTS	PSV
Loa	75	83
Installed power kW	16000	7000
Winch capacity (tonnes)	300	...
Propulsion system	DE hybrid	DE
Crane capacity (tonnes)	10	....
Fuel type	MGO+LNG	MGO
Operational region	North Atlantic	East China sea
Ship owner country	Norway	Singapore
Building Yard	Norway	China
Design team location requirement	Norway	Norway-China
Class society	DNVGL	CCS
Designers experience in the segment (number of designed vessel in segment)	3	3
Annual turn over of owner (MUSD)	30	500
Size of ship owner (# of employees)	45	1200
Annual changes in NB contracting activity	3 %	-2 %
Total vessel price	45 MUSD	28 MUSD
Expected value creation (selling design and main equipment package)	15 MUSD	12 MUSD

Relevant complexity factors of the two ship design projects were calculated based on the items listed in Figure 6 and explained methodology. The results show design project P1 has higher structural and behavioural complexity. Although due to local customer, local class society, and local building yard to build the project, this project appears to have less perceptual complexity issues. The spatial complexity of the process is higher for the project in China since a distributed design team is needed to support the building yard. Design experience is similar in both vessel segments, however, due to more powerful shipowner (larger size and higher turnover) expected decision-making complexity is higher for the P2 project. Annual newbuilding contracting changes show less complex market situation for project P1 compared to project P2. This means the design firm can think of further similar projects in positive market trends. By such evaluations of different complexity aspects, it is concluded that design project P1 is less complex compared to P2. Although considering only product related complexity aspects, design project P1 deals with more complex product compared to P2. Design firm X can evaluate project complexity versus value creation for prioritization among the projects in complexity -value matrix (Figure 14). Typically design projects with less complexity and high value creation are the most favourable design projects (Lawley, 2010). In this case, the design project P1 to be built in Norway is positioned in the most favourable zone due to its relatively lower complexity and higher value creation. Therefore, this project based on the defined premises of less complexity and more value creation can be the priority for the design firm. However, depending upon the changes in the design project condition or value creation, project prioritization can change. For instance, if the scope of the project P1 was limited to selling concept and basic design with the value creation of 1 MUSD, then the picture substantially changes and design project P2 can be a more interesting by accepting all extra complexities.

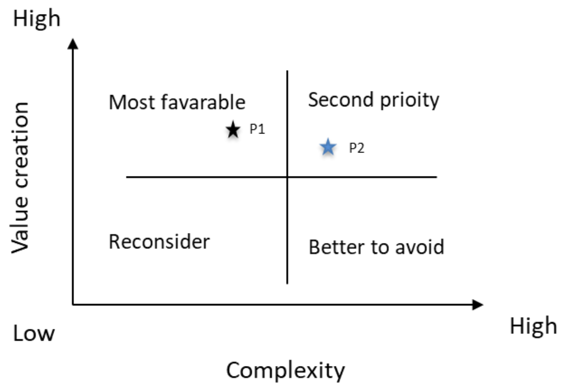


Figure 14: Complexity-value matrix adapted from (Lawley, 2010)

5. DISCUSSION AND CONCLUSION

In this article, several of the different complexity measurement methods presented in the generic engineering design and ship design literature have been reviewed. Their relevance and applicability in daily ship design practices have been examined. Different measures to include the influence of product-, process-, or firm- related complexity factors are elaborated in some detail in this paper. Available indexes quantifying structural complexity, the information content of the design, visual complexity, technological complexity, spatial complexity, or shape complexity are explained with the support of some case studies from offshore vessels and cruise ship vessel design projects. We also reviewed other more frequently used ship design complexity measurements methods, such as CGT, and its validity and relevance to this research study. New complexity compensation coefficients to differentiate between different offshore vessel subtypes were developed and introduced in this paper by using construction data from Ulstein-built vessels.

The result of our study revealed that each of the measurement methods in the literature addresses one or two product-related aspects of complexity, but not all. Therefore, our proposition was supported that there is a need for a method to integrate different complexity factors in a new model to quantify ship design complexity. The new comprehensive model to quantify ship design complexity is developed in this research work based on the nine different descriptive factors model. Based on our findings, it is argued that it is possible to quantify ship design complexity in the concept design phase. However, such methods should not be confined only to product-related structural or behavioural issues. To measure complexity, it is required to understand and quantify different aspects reflecting product, process, and the firm.

Different complexity factors are explained, and items constituting each factor and relevant measurement approach are documented in some detail in this research work. The complexity measurement model was applied on 486 offshore vessels, representing 100 designs, designed by eight major Norwegian design firms. It is shown that quantified value for different complexity factors can vary from design to design and from one design firm to another depending upon differences in technical parameters, design process, organization, and market situation. It is also presented how comprehensive complexity measurement model can be useful in the upstream vessel design evaluation phases. The method was used to quantify the complexity of two ship design projects for prioritization purposes. A quadrant complexity versus value creation matrix is suggested for ranking purposes.

This study has limitations since it is confined to the offshore vessel segment, and only Norwegian design firms. Expanding the method to other vessel segments and more global ship design firms could perhaps support the validity of the suggested measurement model. In the developed measurement model, four to five items are used to measure each complexity factor. These results might change by adding new item or removing one of the items from each factor. The statistical method Cronbach's alpha (Hair et al., 2010) is used in this study to verify the reliability and consistency of the items inside each factor. The loadings of each item on different complexity factors are also measured in separate confirmatory factorial analysis. Identifying and measuring complexity factors by a new comprehensive model, as presented in this paper, is used as a primary step for future research. The goal for future research is to understand the effect of each complexity factor on the competitiveness of a ship design. Such an understanding is a prerequisite for ship design practitioners and ship design firms to select appropriate strategies to handle the complexity in ship design and eventually enhance their competitiveness.

6. REFERENCES

1. ALABDULKAREEM, A., ALFARIS, A., SAKHRANI, V., ALSAATI, A., & WECK, O. DE. (2013). *Framework (MHIF) for Modeling Complex Engineering Systems*. Complex Systems Design & Management, 301–313. https://doi.org/10.1007/978-3-319-02812-5
2. AMAH, E., DAMINABO-WEJE, M., & DOSUNMU, R. (2013). *Size and Organizational Effectiveness: Maintaining a Balance*. Advances in Management & Applied Economics, *3*(5), 115–123. http://www.scienpress.com/Upload/AMAE/Vol 3_5_8.pdf
3. ANDREWS, D. J. (2011). *Marine requirements elucidation and the nature of preliminary ship design*. International Journal of Maritime Engineering, *153*(1), 23–40. https://doi.org/10.3940/rina.ijme.2011.a1.202
4. ANDREWS, D. J. (2017). *Submarine design is not ship design*. Warship.
5. ANDREWS, D. J. (2018a). *The Conflict Between Ship Design and Procurement Policies*. Warship.
6. ANDREWS, D. J. (2018b). *The sophistication of early stage design for complex vessels*. International Journal of Maritime Engineering, 1–54. https://doi.org/10.3940/
7. AZIM, S. W. (2010). Understanding and Managing Project Complexity. https://www.semanticscholar.org/paper/Understanding-and-Managing-Project-Complexity-Azim/3130e5fa57f829713266d265f594c422302ba059
8. BACKLUND, A. (2002). *The concept of complexity in organisations and information systems*. Kybernetes, *31*. https://doi.org/10.1108/03684920210414907
9. BECZ, S., SE, L., STREET, D., MA, U., PINTO, A., ZEIDNER, L. E., KHIRE, R., BANASZUK, A., & REEVE, H. M. (2010). *Design System for Managing Complexity in Aerospace Systems*. AIAA ATIO/ISSMO Conference, 1–7.
10. BENEDETTINI, O., & NEELY, A. (2012). *Factors Influencing Service Complexity : The Perspective of Servitized Manufacturers Factors Influencing Service Complexity :* EurOMA Conference 2012.
11. BLOOMBERG. (2020). *Bloomberg*. https://www.bloomberg.com/profile/company
12. BODE, C., & WAGNER, S. M. (2015). *Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions*. Journal of Operations Management, *36*, 215–228. https://doi.org/10.1016/j.jom.2014.12.004
13. BRAHA, D., & BAR-YAM, Y. (2007). *The Statistical Mechanics of Complex Product Development: Empirical and Analytical Results*. Management Science, *53*(7), 1127–1145. https://doi.org/10.1287/mnsc.1060.0617
14. BRETT, P. O., CARNEIRO, G., HORGEN, R., KONOVESSIS, D., OESTVIK, I., & TELLKAMP, J. (2006). *LOGBASED: Logistics-Based Ship Design*. International Marine Design Conference (IMDC).
15. BROEKEL, T. (2017). *Measuring technological complexity - Current approaches and a new measure of structural complexity*. Mathematics, Physics ArXiv: Applications. http://arxiv.org/abs/1708.07357
16. BUDDE, L., NAGLER, O., & FRIEDLI, T. (2015). *A method to set up a complexity index to improve decision-making*. Procedia CIRP, *36*, 53–58. https://doi.org/10.1016/j.procir.2015.01.052
17. CAPRACE, J. D., & RIGO, P. (2012). *A real-time assessment of the ship design complexity*. CAD Computer Aided Design, *44*(3), 203–208. https://doi.org/10.1016/j.cad.2010.12.005
18. CESA EU. (2018). *CESA EU*. https://www.cesa.eu/
19. EBRAHIMI, A., BRETT, P. O., ERIKSTAD, S.

O., ASBJØRNSLETT, B. E., & GARCIA, J. J. (2021). *Ship design complexity, sources, drivers, and factors: A literature review*. International Shipbuilding Progress.

20. EBRAHIMI, A., BRETT, P. O., & GARCIA, J. J. (2018). *Managing complexity in concept design development of cruise- exploration ships*. International Marine Design Conference (IMDC), 569–577.

21. EFTHYMIOU, K., MOURTZIS, D., PAGOROPOULOS, A., & PAPAKOSTAS, N. (2016). *Manufacturing systems complexity analysis methods review*. International Journal of Computer Integrated Manufacturing, *29*(9), 1025–1044. https://doi.org/10.1080/0951192X.2015.1130245

22. ELMARAGHY, H. A., KUZGUNKAYA, O., & URBANIC, R. J. (2005). *Manufacturing systems configuration complexity*. CIRP Annals - Manufacturing Technology, *54*(1), 445–450. https://doi.org/10.1016/S0007-8506(07)60141-3

23. ELMARAGHY, W., ELMARAGHY, H., TOMIYAMA, T., & MONOSTORI, L. (2012). *Complexity in engineering design and manufacturing*. CIRP Annals - Manufacturing Technology, *61*(2), 793–814. https://doi.org/10.1016/j.cirp.2012.05.001

24. FOR, O. D., & SCIENCE, T. AND I. (STI). (2007). COMPENSATED GROSS TON (CGT) SYSTEM.

25. GASPAR, H. M., RHODES, D. H., ROSS, A. M., & ERIKSTAD, S. O. (2012). *Addressing Complexity Aspects in Conceptual Ship Design : A Systems Engineering Approach*. Journal of Ship Production and Design, *28*, 145–159.

26. GASPAR, H. M., ROSS, A. M., RHODES, D. H., & ERIKSTAD, S. O. (2012). *Handling Complexity Aspects in Conceptual Ship Design Conceptual Ship Design ; Systems Engineering ; Handling Complexity Information Growth in Ship Design*. International Marine Design Conference (IMDC), *June*.

27. HAIR, J. F., BLACK, W. C., BABIN, B. J., & ANDERSON, R. E. (2010). Multivariate Data Analysis. https://doi.org/10.1016/j.ijpharm.2011.02.019

28. HORNBY, G. S. (2007). *Measuring Complexity by Measuring Structure and Organization*. EEE Congress on Evolutionary Computation. https://doi.org/10.1109/CEC.2007.4424721

29. HUIJGENS, L. J. G. (2016). Quantification of Manufacturing Complexity in Shipbuilding Projects. resolver.tudelft.nl/uuid:34ffb7d9-91a6-412e-aa14-07e23c389666

30. IHLEN, Ø., & VERHOEVEN, P. (2017). *Organization-society relationship*. The International Encyclopedia of Organizational Communication, *March*, 1–9. https://doi.org/10.1002/9781118955567.wbieoc157

31. IHS FAIRPLAY. (n.d.). World Register of Ships. IHS Markit.

32. JACOBS, M. A. (2013). *Complexity : Toward an empirical measure*. Technovation, *33*(4–5), 111–118. https://doi.org/10.1016/j.technovation.2013.01.001

33. KOHR, D., BUDDE, L., & FRIEDLI, T. (2017). *Identifying Complexity Drivers in Discrete Manufacturing and Process Industry*. Procedia CIRP, *63*, 52–57. https://doi.org/10.1016/j.procir.2017.03.290

34. KOLMOGOROV, A. N. (1998). *On tables of random numbers*. Theoretical Computer Science, *207*(2), 387–395. https://doi.org/10.1016/S0304-3975(98)00075-9

35. KULAK, O. (2005). *A decision support system for fuzzy multi-attribute selection of material handling equipments*. Expert Systems with Applications, *29*(2), 310–319. https://doi.org/10.1016/j.eswa.2005.04.004

36. KUMARI, M., & KULKARNI, M. S. (2016). *A complexity based look-ahead mechanism for shop floor decision making*. Procedia CIRP, *41*, 63–68. https://doi.org/10.1016/j.procir.2015.12.032

37. LAWLEY, B. (2010). The Four Quadrant Feature Prioritization Matrix (Kindle Edition (ed.)).

38. LEVIN, I. P., WELLER, J. A, PEDERSON, A. A, & HARSHMAN, L. A. (2007). *Age-related differences in adaptive decision making: Sensitivity to expected value in risky choice*. Judgment and Decision Making, *2*(4), 225–233. http://journal.sjdm.org/7404/jdm7404.htm

39. LIAO, Z. (2016). *Temporal cognition, environmental innovation, and the competitive advantage of enterprises*. Journal of Cleaner Production, *135*, 1045–1053. https://doi.org/10.1016/j.jclepro.2016.07.021

40. LINDEMANN, U., MAURER, M., & BRAUN, T. (2009). Structural Complexity Management: An Approach for the Field of Product Design. Springer Berlin Heidelberg. https://books.google.co.uk/books?hl=en&lr=&id=O9QYYtOAZ0IC&oi=fnd&pg=PP5&dq=the+downfalls+of+design+structure+matrix&ots=YHitZolXgy&sig=xMOTSIysXGVep95hT25Cs9S71vY#v=onepage&q=DSM&f=false

41. *Linkedin webpage*. (2020). https://no.linkedin.com/

42. LUZEAUX, D. (2013). *SoS and Large-Scale Complex Systems Architecting Adapting to a Changing Environment A Particular Field : Defense*. Complex Systems Design & Management, 39–49. https://doi.org/10.1007/978-3-319-02812-5

43. MAURER, M. (2017). Complexity Management in Engineering Design – a Primer. Springer Vieweg. https://doi.org/10.1007/978-3-662-53448-9

44. MAURER, M., & LINDEMANN, U. (2007). *Facing Multi-Domain Complexity in Product Development*. Competence in Design and Development (CiDaD), *03*(01), 1–12.

45. MOCKO, G. M., & PORTER, M. (2008). *Engineering design complexity : an investigation of methods and measures*. Research in Engineering Design, 161–179. https://doi.org/10.1007/s00163-008-0053-2
46. OECD DIRECTORATE FOR SCIENCE, T. AND I. (S.). (2007). Compensated gross ton (CGT) system.
47. OLIVA, A., MACK, M. L., SHRESTHA, M., & PEEPER, A. (2004). *Identifying the Perceptual Dimensions of Visual Complexity of Scenes*. Proceedings of the Twenty-Sixth Annual Conference of the Cognitive Science Society, *26(26)*, 1–6.
48. PAPANIKOLAOU, A. (2010). *Holistic ship design optimization*. Computer-Aided Design, *42*(11), 1028–1044. https://doi.org/10.1016/j.cad.2009.07.002
49. PORTER, M. E. (1985). Competitive Advantage: Creating and Sustaining Superior Performance.
50. *Proff the business finder*. (2020). www.proff.no
51. QUSAIBATY, A., HOWARD, N., & ROLLAND, C. (2004). *Process Complexity: Towards a Theory of Intent-oriented Process Design*. Framework. http://cogprints.org/4877/
52. REMINGTON, K., & POLLACK, J. (2008). Tools for Complex Projects (1st Editio). Gower Publishing.
53. RHODES, D. H., & ROSS, A. M. (2010). *Five Aspects of Engineering Complex Systems Emerging Constructs and Methods*. Annual IEEE Systems Conference.
54. SALINGAROS, N. A. (2014). *Complexity in Architecture and Design*. Oz Journal, Volume 36, May 2014, Pages 18-?-25 Introduction, *36*(May), 1–13.
55. SAN CRISTÓBAL, J. R., CARRAL, L., DIAZ, E., FRAGUELA, J. A., & IGLESIAS, G. (2018). *Complexity and project management: A general overview*. Complexity, *2018*. https://doi.org/10.1155/2018/4891286
56. SCHUH, G. (2016). *Approaach to evaluate complexity in new product development projects*. International Journal of Design & Nature and Ecodynamics, *11*(4), 573–583. https://doi.org/10.2495/DNE-V11-N4-573-583
57. SIMON, H. A. (1973). *The structure of ill structured problems*. Artificial Intelligence, *4*(3–4), 181–201. https://doi.org/10.1016/0004-3702(73)90011-8
58. ŞTEFAN, R.-M. (2012).*A comparison of data classification methods*. Procedia Economics and Finance, *3*(12), 420–425. https://doi.org/10.1016/s2212-5671(12)00174-8
59. SUH, N. (1990). The Principles of Design. Oxford University Press.
60. SUH, N. P. (2001). Axiomatic Design. Advances and Applications. Oxford University Press.
61. SUH, N. P. (2005). *Complexity in engineering*. CIRP Annals, *54*(2), 46–63. https://doi.org/10.4324/9780203871393
62. TANI, G., & CIMATTI, B. (2008). *Technological complexity: A support to management decisions for product engineering and manufacturing*. 2008 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2008, 6–11. https://doi.org/10.1109/IEEM.2008.4737822
63. TAUHID, S., & OKUDAN, G. (2007). *Fuzzy information axiom approach for design concept evaluation*. International Conference on Engineering Design, ICED'07 28 - 31 August 2007, Cite Des Sciences Et De L'industrie, Paris, France., *August*, 1–12. http://m.designsociety.org/download-publication/25341/fuzzy_information_axiom_approach_for_design_concept_evaluation
64. TURYAKIRA, P., VENTER, E., & SMITH, E. (2014). *The impact of corporate social responsibility factors on the competitiveness of small and medium-sized enterprises*. South African Journal of Economic and Management Sciences, *17*(2), 157–172. https://doi.org/10.4102/sajems.v17i2.443
65. Ulstein segment vessel data basis. (2020).
66. ULSTEIN, T., & BRETT, P. O. (2012). *Critical Systems Thinking in Ship Design Approaches*. International Marine Design Conference (IMDC).
67. VINODH, S., KAMALA, V., & JAYAKRISHNA, K. (2015). *Application of fuzzy axiomatic design methodology for selection of design alternatives*. Journal of Engineering, Design and Technology, *13*(1), 2–22. https://doi.org/10.1108/JEDT-02-2013-0017
68. WU, K., VASSILEVA, J., ZHAO, Y., NOORIAN, Z., & WALDNER, W. (2016). *Complexity or simplicity ? Designing product pictures for advertising in online marketplaces*. Journal of Retailing and Consumer Services, *28*, 17–27. https://doi.org/10.1016/j.jretconser.2015.08.009

APPENDIX A

We applied Reangularity and Semiangularity measures on the design of a simple deck barge. The intention was to examine the applicability of the method to measure complexity of ships. The measurement method was applied on the two solutions of a typical deck barge (Fig 1a) and a decoupled barge solution (Fig 1b). The decoupled solution is a combination of the two pontoons with flexible distance (Bp) to adjust the stability. The size of the pontoons is also adjustable due to displacement need. The results were compared to each other to demonstrate the effectiveness of the measures in quantifying structural complexity of the two vessel design solution.

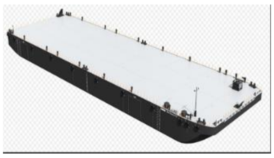


Fig 1a) Simple deck barge

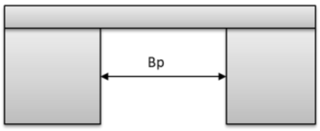


Fig 1b) Decoupled solution cross section

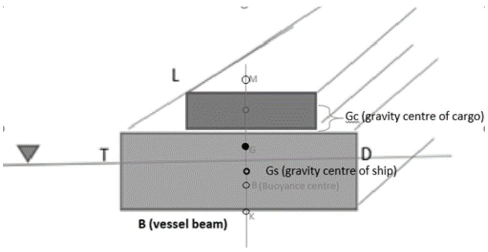
Table 1 shows the functional requirement and design parameters for the decoupled solution. A similar table was also developed for the normal barge. The vessel main dimensions include: Length(L), Beam (B), Depth (D) and Draft (T), distance between pontoons (Bp), gravity centre (Gc). Minimum in required GM for stability is designed at 1,5m. Based on similar ships: T=0,7 * D for barges is used to simplify the calculations.

Table 1) Functional requirements and design parameters

	Functional requirements	Design parameters	Mathematical formulation
1	Enough deck cargo space	f (Bp, B)	Cargo Area = $2*(2B + Bp)^2$ (1)
2	Sufficient displacement (Δ)	f (L, B, D)	Δ= 1,4*L*B* D (2)
3	Low steel weight	f (L,B,D)	$St\ weight\ for\ 2\ pontoons = 0{,}066\ L^{1{,}6}\ B\ D^{0{,}22}$ (3)
4	Permissible stability	f (L,B,D,Gc)	Mathematical model Eq2

Total gravity centre of the vessel depends on the light weight of the vessel, transverse position of its gravity centre and the height of the cargo. In this case for simplification steel weight and the lightship weight are assumed equal. Vessels do not have any equipment installed. Stability parameters are illustrated on Figure 2 for typical simple deck barge. The important element of intact stability of the ship is the distance between total gravity centre and meta centric height of the vessel (GM).

Figure 2: stability parameters on simple deck barge



Gs= D/2 gravity centre of the barge (4)

Gc: gravity centre of the cargo on deck and KG: Vessel full load gravity centre

KG = ((Stw * Gs) + (cargo weight * (Gc+D)))/Displacement (5)

Cargo weight = Displacement – Steel weight (6)

Based on a linear regression model on typical deck barges, steel weight can be estimated by equation (7) for simple deck barge solution.

Steel weight of deck barges = 0.22 * Displacement – 345 (7)

$$\begin{cases} BM = \frac{B^2}{0{,}7*12*D} \\ KB = \frac{0{,}7\ D}{2} \end{cases} \quad (8)$$

By implementing equations (6) and (7) inside equation (5) and further mathematical simplifications the expression for gravity centre of the barge is determined as equation (9).

$$KG = \frac{492*Gc}{L*B*D} + \frac{246}{L*B} + 0.89*D + 0.78*Gc \quad (9)$$

$$GM = KB + BM - KG \quad (10)$$

By using equations (4,9,10), the mathematical expression to calculate the GM is extracted as Equation (11) for simple deck barge

.

$$GM = \frac{B^2}{8{,}4\ D} - \frac{492*Gc}{L*B*D} - \frac{246}{L*B} - 0{,}43D - 0.78\ Gc \quad (11)$$

Similar calculations were also conducted for a decoupled barge solution. According to mathematical models the functional requirement (FR) and the design parameter (DP) matrix (a,b) were developed for both solutions to show the level of couplings among FR's as well as FRs and DPs in the solutions.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{Bmatrix} L \\ B \\ D \\ Gc \end{Bmatrix} \qquad \begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} L \\ B \\ D \\ Bp \end{Bmatrix}$$

a) Design matrix for simple barge b) Design matrix for solution 2

There is cross-correlation between DPs and FRs in the design matrix. In addition, due to mathematical formulation of the design parameters, interdependencies between DPs is also noticed. Reangularity and

Semiangularity indexes are calculated as follows for simple deck barge case.

$$\begin{Bmatrix} dFR1 \\ dFR2 \\ dFR3 \\ dFR4 \end{Bmatrix} = \begin{Bmatrix} \frac{\partial F_1}{\partial L} & \frac{\partial F_1}{\partial B} & \frac{\partial F_1}{\partial D} & \frac{\partial F_1}{\partial G_C} \\ \frac{\partial F_2}{\partial L} & \frac{\partial F_2}{\partial B} & \frac{\partial F_2}{\partial D} & \frac{\partial F_2}{\partial G_C} \\ \frac{\partial F_3}{\partial L} & \frac{\partial F_3}{\partial B} & \frac{\partial F_3}{\partial D} & \frac{\partial F_3}{\partial GC} \\ \frac{\partial F_4}{\partial L} & \frac{\partial F_4}{\partial B} & \frac{\partial F_4}{\partial D} & \frac{\partial F_4}{\partial GC} \end{Bmatrix} \begin{bmatrix} dL \\ dB \\ dD \\ dG_C \end{bmatrix} =$$

$$\begin{bmatrix} B & L & 0 & 0 \\ 0,7BD & 0,7LD & 0,7LD & 0 \\ 0,053B^{0,22}\,DBL^{0,6} & 0,033L^{1,6}\,D^{0,2} & 0,007L^{1,6}\,BD^{0,78} & 0 \\ \frac{492G_c}{L^2\,BD} + \frac{246}{L^2\,B} & \frac{492G_c}{B^2\,L\,D} + \frac{246}{B^2\,L} & \frac{492G_c}{LBD^2} + \frac{B^2}{8,4\,D^2} - 0,43 & \frac{-492}{LBD} - 0,78 \end{bmatrix}$$

The design matrix is normalized by dividing differentials to FR $\mathrm{d}\widehat{F}_i = \frac{\mathrm{d}F_i}{F_i}$ for i: 1 to 4. After normalization, design parameters in the design matrix are replaced by a unit value of 1, to calculate Reangularity and Semiangularity of the design.

$$\mathrm{DM} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1,6 & 1 & 0,22 & 0 \\ -0,98 & -0,98 & -0,66 & 0,66 \end{bmatrix}$$

$$S = \prod_{j=1}^{n} \left(\frac{|A_{ij}|}{\left(\sum_{k=1}^{n} A_{kj}^2\right)^{0.5}} \right) = 0.037$$

In the same way values from design matrix are used to calculate Reangurity

$$R = \prod_{\substack{i=1,n-1 \\ J=i+1,n}} \left(1 - \frac{\left(\sum_{k=1} A_{ki} A_{kj}\right)^2}{\left(\left(\sum_{k=1}^{n} A_{k_i}^2\right) * \left(\sum_{k=1} A_{k_j}^2\right)\right)} \right)^{0.5} \quad ; \quad R = 0.16$$

Low values of R and S in the first design solution, shows high degree of coupling between design parameters and functional requirements where DP’s are also internally coupled to each other. Such an observation shows that even a simple deck barge is rather a complex and a coupled product. The level of such product complexity dramatically increases by moving towards more advanced ships with different functionalities onboard. In such vessels any small changes in one of the design parameters can influence several functional requirements simultaneously.

Visual observations of design matrix b present less cross-correlations in solution 2 compared to solution 1. To determine the level of interdependencies and couplings between FRs and DPs, R and S also are calculated for this solution based on a similar method as explained for solution 1. The calculated value of R and S for this solution are 0,6 and 0,12 respectively. These results of the R and S calculation shows higher Reangularity and Semiangularity for solution 2 compared to solution 1. That means solution 2 has less structural complexity in contrast to solution 1 according to the definition of the indexes. Figure 3 compares the value of R and S and Figure 4 shows the number of interconnections between FR’s and DP’s among the two solutions based on design matrixes. Less number of interconnections in the matrix 2, is supported by calculated R and S in this case.

Reangularity(R) and Semiangularity(S) are two indexes developed to determine the level of interdependency between functional requirements and cross correlation between functional requirements (FRs) and design parameters (DPs), as measures of structural complexity. The way these measures are formulated requires a mathematical equation of different functional requirements and design parameters as a function of different design variables and their due derivatives. Developing such advanced equations and application of relevant mathematics in design matrixes as it is shown for a simple barge, is almost impossible or at least is an extremely time-consuming task for more advanced vessels, and that will not take place in a real design practice. The result of this study and calculated R and S, support the hypothesis, developing cross correlation matrix between FRs and DPs in its generic level (1-0 matrix), still is a valid indicator to compare the level of couplings and structural complexity between different designs. In such circumstances, the design with higher number of interdependencies between DPs and FRs (higher population of 1 values) in the developed correlation matrix will have generally lower R, and S calculated values which means more coupled/complex solution.

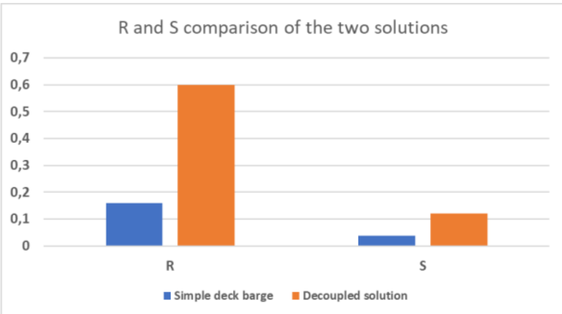


Figure 3: Calculated R and S values for both solutions

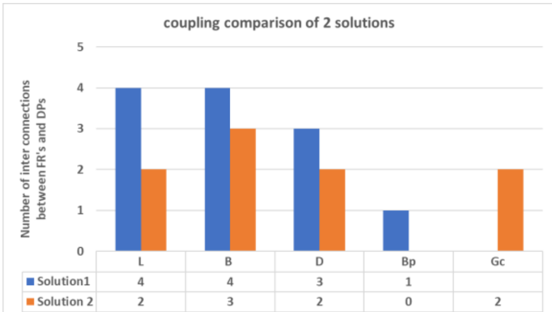


Figure 4: Comparing level of couplings in design matrix for two solutions

Appendix B

The following steps are followed to calculate the complexity factors for different design solutions in the database. From the calculated database for all vessels, seven random design classes are selected and presented in use-case 1.

1- Excel spreadsheet with 95 features as shown in Table 1 of this appendix, was developed for all 486 vessels in the study (486* 95 matrix).
2- Similar design names were combined as one design family, including all variants. The gathered data for Design A 01 (Table 4, of the article) is shown as an example in Table 1 of this appendix. This design is sold 4 times to 2 different customers. The specific names are anonymized in the table due to the confidentiality of the data.
3- Firm information (number of employees, turnover) for 20 years of study period are gathered as extra information from different sources referenced in this article.

Table 1: Gathered technical and commercial data for all variants of design A01

1	2	3	4	5	6	7	8	9	10	11
Primary mode	Operator	Region	Country	Status	Contract date	Designer	Engine Manufacturer	Building Yard	Building Country	LOA
IMR	Owner 02	Australia	Australia	In operation	01.10.2005	Design firm A	Wartsila	Yard 02	Norway	105,9

12	13	14	15	16	17	18	19	20	21	22	23	24	25
LBP	Beam	Depth	LBD	Max. Draft	Dwt	Equipment weight	Free deck area (m2)	Deck Load (Tonnes)	Max. Speed (knots)	Engines total power (hp)	Engine_KW_Total	Gt	CGT
94,7	21,0	8,5	18903,2	6,6	4000	2925	1120	2000	14	15436,8	11520	7051	12356

26	27	28	29	30	31	32	33	34	35	36	37	38
Max static lift capacity (tonnes)	Lift function	Radius max lift cap.	Moon Pool Area	DIV index	Dive system depth rating (m)	Number of bels	Number of hyperbaric chambers	Max pipe diameter (inch)	Max pipe installation depth (m)	Carousel capacity (Tonnes)	cable index	Pipe tensioner capacity (tonne)
140	1	10	51,84	0	0	0	0	0	0	0	0	0

39	40	41	42	43	44	45	46	47	48	49	50
Pipe Index	DP Ind	Accommodation capacity (people)	Max working crane water depth (m)	ROV support	Well interventi on	MH tower capacity (Tonnes)	ERN number	A-Frame (Tonnes)	Gangway	Bollard Pull (Tonnes)	Ice Class
0	2	100	2000	2	0		99,99,93	20	No		FS Ice Class 1B

51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
Subtype	Original owner	Founded	Employee	Turne over	Size variation Loa	LBp	Size variation B	Size variation D	Size variation T	Size variation DWT	Size variation GT	variation kW	variation Speed	Acc Size	BP	Class society diversity
IMR	Owner 01	1996	40	76 000 000	2,73 %	0,00 %	0,00 %	0,00 %	3,45 %	4,56 %	6,00 %	40,00 %	7,15 %	0,00 %	0,00 %	2

68	69	70	71	72	73	74	75	**76**	**77**	**78**
Design development year	last contract year	Number of size variants	Number of sales	Customer diversity	Country of owner (Norway :1 , Mixed 2, only international 3)	Country of owner diversity	Country of built (Norway :1 , Mixed 2, only international 3)	**Country of built diversity**	**Diversity of build yards**	**Type of support functions**
2005	2005	2	4	2	2	3	3	**2**	**2**	**1**

79	**80**	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**
Speed variations	**Power installed**	**Ice cap (no, yes, mixed)**	**Ice capability diversity**	**DE**	**ME**	**Power plant (DE, ME)**	**Engine brand**	**Engine speed**	**Type propulsor**	**Functional diversity in design class**	**percent in service 2015**	**percent in service 2019**	**Design development year**	**Design firm stablishement year**
2	**2**	**1**	**2**	**1**	**0**	**1**	**2**	**2**	**2**	**IMR, Support vessel,**	**100,00 %**	**100,00 %**	**2005**	**2000**

Table 2: Calculated complexity items and factors based on collected data

Directional				Spatial			
A1: Nomber employee	A2-society (ag	A3-major organizational change (score)	A4-Rules changes at the time	B1: Owning several design office in different location	B2: Diversity of building yard for same design	B3:Diversity of countries build similar design	B4: system density (Lwt/ L*B*D)
4	5	2	1	2	1	1	0,28

Decision making						Structural				
C1-Designer knowledge domain	C2-Customer turn over (MNOK	C3-customer Nos employ	C4-customer age	C5-customer Nos vessel in the offshore segment (score)	C6-potential competitor design (score)	D1:Size variation of similar desi	D2: CGT/GT	D3: Main equipment brand diversity	D4:vessel size (Gt*Power	D5: number of different functions installed
1	76		9	1	5	3	1,75	4	81228	5

System behaviour (functional complexity)							Contextual				
E1:Different fuel type	E2:Main engine speeds	E3: type of propulsion	E4:Different Ice class for similar design (score)	E5: Diversity in main vassel functionality as a same design	E6: Speed variance	E7: Installed power variance	F1: Market situation (total number of ship contracts per year above or below average)	F2: market segment situation	F3: Designers market share	F4: Operational region diversit	F5: Design company turn over
1	1	1	3	1	2	3	4010	165	12	3	8748

Perceptual				Temporal				Technological		
G1: Diversity of customers for similar design (score)	G2: Class society divers	G3: Local or intenrational customer	G4: Local or intenrational building yard	H1: Changes in contracting activity in the segment	H2: New building price index changes the year of contract	H3: Global economic growth rate in the year of contract	H4:Business confidence Index in the year of contract	I1: Specific patent recorded for the design	I2: Power plant (DE, ME)	I3: Dp redundancy level
2	1	2	2	56 %	15,2 %	0,04	100,37	1	2	2

4- Based on the gathered data, all relevant items and complexity factors presented in Figure 6 (main article text) is calculated for 100 design classes. Table 3 of this appendix presents the calculations for each item. Table 2 of this appendix presents the calculated values for each item
5- Values converted to Likert scores from 1-5 based on the distribution as explained in the ‘measuring ship design complexity ‘section of this article. For example, the age of the design firm A at the development of time design A 01 has been 5. According to the age distribution of design firms presented in Figure 8 of this article, this design class belongs to group 1. The complexity score for this group is 5. The younger the design firm, will have less establishment in society and will face more complexity compared to more established experienced design firms.
6- The complexity score for each item is calculated based on step 5.
7- The complexity score for each factor is calculated as the total sum of its items (Equation 10 of this article)
8- Complexity scores for all factors are normalized in the range between 0-20 based on the average, maximum, and minimum value of that factor.
9- Results for 7 random designs are presented in table 4 of this article

Table 3: Calculation method for each item

Complexity factors	Relevant items	Measurement criteria	Value	Source and calculation	Likert scale score
F1-Directional complexity	F1-1 Interaction of organisation with society	Company age in the design development year	5	IHS fairplay- Table 1 (Cell 94-cell 95)	5
	F1-2 Design company size	Number of employees in the year of contract	11	Proff.no	1
	F1-3 Major organisational changes in design company	The number of management changes in the organisation, acquisition and mergers	2	Proff.no	2
	F1-4 Nos. of new rules and regulations coming into place in the year of design	Count of new rules and regulation	1	IMO, SPSS,	1
F2- Spatial	F2-1 Owning several design offices in different locations	Numbers. of design offices in the year of design development	2	Company profile , Proff.no	2
	F2-2 Diversity of building yards for same design	Numbers of different yards building similar design	2	Table 1	1
	F2-3 Diversity of country of build for similar designs	Numbers of different countries building similar design	2	Table 1 (Cell 76)	1
	F2-4 Product density	Equipment weight/ L*B*D ratio	0.16	Table 1 (Cell 18/(Cell11* Cell 13 * Cell14)	4
F3- Decision-making complexity	F3-1 Domain knowledge of design firm	Number of recorded designs by design firm in the segment before the new contract	3	IHS fairplay - releveant data is analyzed and extracted	5
	F3-2 Customer's financial power	Annual turnover in the year of contract (MUSD)	76	Proff.no	2
	F3-3 Customer size	Number of employees	40	Proff.no	3
	F3 -4 Customer level of stabalishment and experience in society	Customer age	9	Table 1 (Cell 94 -cell 53)	2
	F3-4 Operational knowledge of customer	Number of vessels in the offshore fleet in the year of contract	3	IHS fairplay, company profile	1
	F3-5 Potential competitors	Number of vessels in similar size and function from other designers in the market in the year of contract	5	IHS fairplay - releveant data is analyzed and extracted	2
F4- Structural complexity	F 4-1 Vessel size	GT (gross tonnage)* Installed power	8,1E+07	Table 1 (Cell 123* Cell 24)	1
	F 4-2 Functional multititde	Number of different offshore support functions installed	5	Table 1 (Number ROV+ Cable lay+ Dive system + A frame + Cable lay + other relevant function)	3
	F 4-3 Design class size diversity	Main dimension variations inside each design class	2	Table 1 (Cell 70 = count of variations in cells 56-62) - 4 vessels with similar design name in the IHS fairplay contracted to different	5
	F 4-4 Construction complexity	CGT (compensated gross tonnage)/GT (gross tonnage)	1,7	Table 1 (Cell 25/ Cell 24)	3
	F 4-5 Brand choice diversity	Number. of different main equipment brands used to construct similar design	4	Table 1 (Cell 86 * Cell 88)	4
F5- Behavioural complexity	F 5-1 Propulsion system diversity	Number of different propulsion system types in similar design class (diesel electric, diesel mechanic, hybrid configuration)	2	Table 1	2
	F 5-2 Design class functional diversity	Number. of different subtypes registered for design class	2	Table 1	3
	F 5-3 Design speed variation	Design speed variation inside each design class	2	Table 1	2
	F 5-4 Installed power variation	Installed power variation inside each design class	3	Table 1	3
	F 5-5 Ice class diversity	Different ice class registered for designs inside design class	3	Table 1	3
F6- Contextual complexity	F 6-1 General maritime market situation	Total number of NB contracts in the year of contract	4010	IHS fairplay	4
	F 6-2 Segment situation	Total number of NB contracts in the same segment	165	IHS fairplay	2
	F 6-3 Designers general market share	Number of sold designs up to the year of contract by designer	12	IHS fairplay - releveant data is analyzed and extracted	5
	F 6-4 Environmental diversity	Beaufort scale of region/ERN (environmental regulatory number) differences among designs	3	Table 1 -Cell 46 - scale based on ERN number	3
	F 6-5 Financial status of designer	Design company turn over in the year of contract (MUSD)	1,8	Proff.no	5
F7- Perceptual complexity	F 7-1 Customer diversity	Number. of different customers	2	Table 1 - Cell 72	1
	F 7-2 Classification society and rules diversity	Number of different class societies selected for designs inside one design class	2	Table 1 - Cell 67	1
	F 7-3 Communication simplicity between designer and customer	Local or international customer or both for designs inside one design class	3	Table 1 - Cell 73	2
	F 7-4 Communication simplicity between designer and building yard	Local or international building yard or both for designs inside one design class	3	Table 1 - Cell 74	2
F8- Temporal complexity	F 8-1 Market trends - more positive trends less complexity	Changes in annual contracting activity in the year of contract	56 %	Figure 12 - Article	2
	F 8-2 Shipbuilding price changes	New building price index in changes the year of contract	15,20 %	Figure 12 - Article	1
	F 8-3 Global business situation - better situation less complexity	Business confidence index in the year of contract	100,37	Figure 12 - Article	4
	F 8-4 Global economy situation- better situation less complexity score	Global economic growth rate in the year of contract	0,04	Figure 12 - Article	2
F9- Technological complexity	F 9-1 New technologies used	Number of patents recorded for the design	1	Design shape related patent	2
	F 9-2 Power plant technological advancement	Diesel electric, diesel mechanic, hybrid or any other advanced type plants	2	IHS fairplay- vessel fact sheet - Table 1	3
	F 9-3 Redundancy level of dynamic positioning system	DP level (DP1, DP2, DP3) – higher DP redundancy is given higher technological	2	IHS fairplay- vessel fact sheets - Table 1	3