The influence of ship design complexity on ship design competitiveness

Ali Ebrahimi[a,b], Per O. Brett[a,b], Stein O. Erikstad[a] , Bjorn E. Asbjørnslett[a]

[a] *Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway*

[b] *Ulstein International AS, Ulsteinvik, Norway*

Complexity is discussed in design literature mainly through its negative and in some cases positive consequences. This paper critically reviews and elaborates the effects of complexity on competitiveness in ship design, its directionality and magnitude. The paper introduces a model for the measurement of ship design complexity and ship design competitiveness based on predefined factors. Archival data of 100 ship design projects from eight different Norwegian designers are used as case study. Multivariate data analysis techniques are employed to study the research model. The results show a significant correlation between complexity and competitiveness in ship design, where the magnitude and directionality of influence vary among different complexity factors. Our findings provide a basis for enhancing complexity management in ship design.

KEYWORDS: Ship design, Competitiveness, Complexity, Multivariate data analysis, Archival study

INTRODUCTION

Continual technology improvements and market volatility with its associated uncertainties have a significant impact on and partly change ship design customers' expectations. To be successful in such a market, not only does it require the development of competitive products, but the accompanying work processes and the organisation or firm framing the development of the vessel solution are also involved. Ulstein and Brett (2015) define ship design competitiveness in terms of doing the right thing (effectiveness); doing the right thing right (efficiency); with the right resources (efficacy) to cover product, process, and firm aspects of competitiveness. To improve their success, ship design companies typically tend to focus on the introduction of new technologies, and, in some cases, extra functional capabilities, which have led to large and complex vessels over the years. To a lesser extent, ship designers have put emphasis on the overall needs of customers. Securing a higher overall performance yield of the ship design solution compared to peer vessels out in the market is not a common practice among ship designers; they rather focus on a typical and traditional subset of performances. The implications and the consequences of such strategies in ship design have led to a growing need for a new set of design tools and project making skills, a more extensive design process with different disciplines involved, and many iterations in the design development process.

It is argued in the relevant engineering design literature that the emerged complexity in the product and design development process is a situation that ship design and manufacturing companies cannot escape from or neglect. Instead, it is essential for them to deal with such complexity appropriately (Kohr, Budde, and Friedli 2017; Vogel and Lasch 2015; Emrah Asan 2013). Extra functional features and new technologies employed in the design solution can add to the product's competitiveness and strategic advantages. However, such functional increments are normally associated with increased design/system complexity (Maurer, Maik 2007; Schuh 2016). Kotteaku (1995) argues that product complexity also has implications for organisational efficiencies (Kotteaku, Laios, and Moschuris 1995). He explains that high-complexity products require strong links between designer, suppliers, and other external bodies to provide the required initial information. Therefore, commercial complexity increases according to an increased number of people involved in the process and an increased level of communication among the individuals. In general such an extra complexity can lead to productivity loss and rises in complexity cost in the value chain (Kohr, Budde, and Friedli 2017)

In his study, Shulman concludes that extra pre-purchase information reduces competitiveness by negatively affecting consumers' decisions in regard to product purchase or service enrolment (Shulman, Jr, and Clair 2015). Extra complexity, because of decentralised design and manufacturing methods and their influence on competitiveness, has also been investigated in other research. The results suggest that, despite extra associated costs and an enlarged number of communications, competitiveness will be enhanced as a consequence of improved accessibility to new customers and markets (Srai et al. 2016; Broekel 2017). On the contrary, other studies find lower competitiveness for organizations in situations of high spatial complexity as a result of higher logistics costs and less control (Azim 2010). Azim (2010) and Remington (2009) suggest that unshared goals and objectives in the organisation, or organisational instabilities, reduce the effectiveness of the performance of the organisation or ship design project team. Such a reduction in the effectiveness directly influences its competitiveness. Typically, it is argued in the literature that organisational inefficiencies, lack of response capacity or organisational inertia, and even, in the worst cases, business failure might happen due to increased product, process, and firm/organisational complexity if it is not dealt with appropriately (Pina 2010).

There are diverse and most often contradictory arguments regarding the influences of complexity on competitiveness in the literature, as explained. Hence, the main objective of this paper is to explore, investigate, and answer the following research question: How does ship design complexity influence ship design competitiveness? To approach the problem at hand, first we explore the existence of such relationship between these two constructs. Further, the direction and magnitude of the influence are determined. A methodology is introduced to measure the competitiveness of a ship design solution based on the systemic design perspectives of design for effectiveness, design for efficiency, and design for efficacy. This paper defines ship design complexity based on a model developed from a literature search and uses nine descriptive factors of directional, spatial, decision-making, structural, behavioural, contextual, perceptual, temporal, and technological to explain and measure ship design complexity.

RESEARCH MODEL AND APPLIED ANALYTICS METHODS

Research model

In this section, we present an investigative model to explore the research question. Our generic investigative model is presented in Fig. 1. The independent variable ship design complexity contains nine factors extracted from the literature. The dependent variable ship design competitiveness is measured by three main factors of effectiveness, efficiency, and efficacy, as suggested by Ulstein and Brett (2015).

Our research proposition in the form of the null hypothesis (H0) states that there is no correlation between complexity and competitiveness in ship design. It is the task of this research to discredit this hypothesis and prove the relationship between complexity and ship design competitiveness in ship design. An alternative hypothesis in this research states that there is a statistically significant and negative relationship between complexity in ship design and competitiveness. An alternative hypothesis proposes that the greater the intensity of the nine complexity constructs in conceptual ship design, the lower the ship design competitiveness. This means that the lower the complexity in ship design is positively associated with competitiveness in vessel conceptual design processes. The null and alternative hypotheses of this research are examined based on the collected empirical data and the corresponding analysis of this research work. In the next paragraphs, applied analytics methodology is explained.

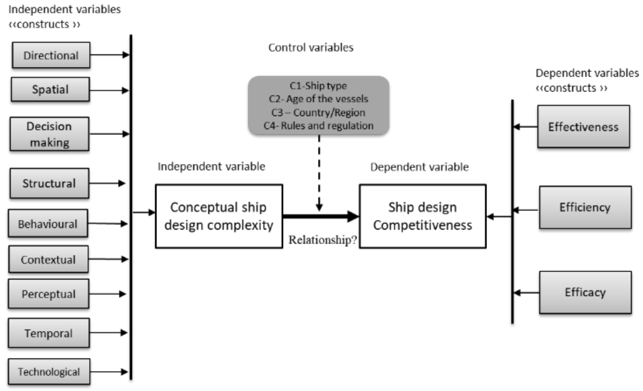

Figure 1: Proposed investigative model

Applied data analytics methods

We have used both a quantitative and a qualitative data analytics method to study and answer the research question. Among the different research methods suggested by Yin (Robert K. Yin - 2002), the analysis of archival information is selected for this research. By selecting this strategy, the research has focused on the past and changes over time using exploratory and explanatory analysis of the reality happening. The empirical study is conducted based on the collected and collated data of 100 offshore vessel designs as study cases. The designs are developed by eight major Norwegian ship designers after 2000 and represent 396 offshore vessels in the market. Several other design cases and anecdotes from daily design practices at Ulstein are also used to develop the arguments and interpretation of the results in this paper. The research analysis is conducted in two main steps of a pilot study and the main study. In the pilot study, 25 design solutions were randomly selected from the database to test and verify the developed methodology and the realism of the results on a smaller scale. Further, based on the experiences and advancements coming from the pilot study, the main research analysis was conducted on the remaining 75 designs of the dataset. The results were compared with those of the pilot study and prepared for the final interpretation and verification of the research model. We have used different multivariate data analysis techniques, including canonical correlation analysis (CCA) and multiple linear regression (MLR) analysis (Hair et al. 2010), to determine the existence and magnitude of the correlation between complexity and competitiveness of ship design in this study.

MLR in this study is used to study and explain the relationship between multiple independent or predictor variables (X), nine complexity factors, and one dependent or criterion variable (Y) of competitiveness in ship design. By applying the method, each of the independent variables will have an effect (magnitude, sign, and statistical significance) on changes in the dependent variable. A basic formulation is presented in Eq. 1. The term b represents the regression coefficients and represent both the type of relationship (whether positive or negative) and the strength of it, and $\boldsymbol{\varepsilon}$ represents the error of analysis or residuals. The results of this study show how the different nine complexity factors influence competitiveness in ship design.

$$\mathrm{Y} = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_n X_n + \varepsilon \qquad (1)$$

CCA is a multivariate analysis of correlation which is a logical extension of the multiple regression analysis. With a canonical analysis, the objective is to simultaneously correlate several metric dependent variables (x1,x2, …, xn) – nine complexity factors in ship design – and several metric independent variables (y1,y2, … yn) – three ship design competitiveness factors – whereas multiple regression involves a single dependent variable (Hair et al. 2010). In this study, we use the canonical method to validate the robustness of the three factors of the dependent construct – effectiveness, efficiency, and efficacy – to measure competitiveness in ship design. Furthermore, we examined if there was any relationship between ship design complexity and competitiveness.

Before discussing the result of the analysis, in the next two sections of this article, the notions of complexity and competitiveness in ship design and their constituting factors and relevant measurement items are explored.

COMPLEXITY IN SHIP DESIGN

Engineering design is a process which starts as a response to a specific need or an inquiry by a customer (NAM.P.SUH 1990). Further, the boundary conditions representing competitors, market situations, supply and demand fluctuations, global economics, rules and regulations, and required contingencies are defined (Baker, Denis 2001). The most important design decisions are taken in the conceptual phase, where the final product architecture, its production process, final cost, and operational performance, are the result of early design phase decisions (Levin et al. 2007). The developed concept is a design proposal that is detailed enough to justify whether it is a proper answer to the task and intention of the business case at hand and show a high probability of realisation and success (Andreasen, Hansen, and Cash 2015).

Among different engineering design fields, ship design is a specific customer-oriented and customer-dominated activity, which is positioned in the category of make-to-order (MtO) or engineer-to-order (EtO) design approaches (Ulstein and Brett 2012). Quite often, ship designs are customised, adapted, and developed for a specific client (van Bruinessen, Smulders, and Hopman 2013; van Bruinessen 2016) and to be operated over a relatively long period of time, such as 20 to 40 years (Keane et al. 2017). Generic design practice is a transformation from expected function/s to a physical object. This transition represents the synthesis activity from 'what needs to be achieved' to 'how to achieve it' (Amro M.Farid; Nam P.Suh 2016) p 9-11. 'What needs to be achieved' in ship design context is a ship design solution, and 'how to achieve it' defines the design process and its context, the firm or its organisation, which needs to be involved to achieve the desired design solution.

The idea of a ship as a complex structure is well established in the field, where, in 1959, Evans addressed the ship as an extremely complex problems (Evans 1959). The complexity of such a product among other things relates to its size, number of components, and internal interactions between the components as well as the dynamics of the context within which the ship design is developed or will be operated. A variety of stakeholders involved in the ship design project with typically unclear, diverse, and in many cases contrary expectations leads to several design choices and alternatives in the conceptual design phase. Therefore, ship design is a complex decision-making process of achieving the right balance among these needs and expectations (Ulstein and Brett 2015). Typically, one design parameter in ship design relates to several functional requirements, where some of the functional requirements are also interrelated. In such circumstances, relatively small changes in the design parameters are typically associated with very large consequences in the resulting performance yield outcomes (Ebrahimi et al., 2015). A new set of skills, tools, software, or technologies in addition to the total required time to finalise a new design also influences the level of complexity in the ship design organisation and process.

In the literature, different aspects/factors of complexity with their relating items are addressed to explain the complexity of ship design. These aspects are typically driven from different sources of product, process, design organisation, and market situation. Structural and behavioural/functional aspects of complexity are discussed most frequently by different ship design practitioners (Mistree et al., 1990; Singer, Doerry and Buckley, 2009; Papanikolaou, 2010; Andrews, 2018). In his study, Gaspar (2012) introduces three more aspects of contextual, temporal, and perceptual complexity in ship design (Gaspar et al. 2012). In the engineering design literature, complexity is typically modelled and measured by information content, such as the Shannon entropy model (Kumari and Kulkarni 2016; Suh 2005), or by the structural complexity of the system or product (Suh 2001; Lindemann, Maurer, and Braun 2009). Measuring complexity based on the number of functions and functional decomposition of a product (Bashir and Thomson 1999) or a graph-based model on the complexity design structure matrix are popular methods suggested in the literature (Shafiei-monfared and Jenab 2012). Other more simplistic methods in the literature suggest to measure the complexity based on the geographical distribution of the design or production facilities (Kohr, Budde, and Friedli 2017), 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 (Qusaibaty, Howard, and Rolland 2004). Existing methods and complexity measurement models use objective data to assess complexity (Efthymiou et al. 2016).

In this study, we use nine descriptive factors of directional, spatial, decision-making, structural, behavioural, contextual, perceptual, temporal, and technological as the main factors influencing ship design complexity (Ebrahimi, Brett, et al. 2021; Ebrahimi, Erikstad, et al. 2021).Table 1 includes the definitions of the nine factors with their references, relevant items, and measurement mechanism for each item (F1–F9). The table is adapted from the literature review study conducted and presented by (Ebrahimi, Brett, et al. 2021) . For each factor, 4 to 5 items were identified and categorised by an expert group at Ulstein. Items are scored between 1 to 5 on a Likert scale based on real measured values. In this study, a quantile classification and standard deviation methods were carried out (Ştefan 2012) to convert the calculated values into a scale score of 1–5. Each complexity factor is calculated as a sum of its relating items (Eq. 2). The internal consistency of the items reflecting similar factors is tested and validated by a Cronbach's alpha measure (Hair et al. 2010). An approach to measure the complexity in ship design based on these descriptive factors is discussed and elaborated more in detail by Ebrahimi et al (2020).

$$Complexity\ factor\ i\ = \sum_{j=1}^{n} Related\ complexity\ items \tag{2}$$

Table 1: The nine complexity factors and relevant items adapted from (Ebrahimi, Erikstad, et al. 2021; Ebrahimi, Brett, et al. 2021)

	Complexity factors	**Definition**	**Relevant items**	**Measurement criteria**
F1	Directional complexity	Unshared goals and goal paths, unclear meanings, and hidden agendas. Ambiguities raised due to multiple potential interpretations of goals and objectives	F1-1 Interaction of organisation with society	Company age in the design development year
			F1-2 Design company size	Number of employees in the year of contract
			F1-3 Major organisational changes in design company	The number of management changes in the organisation, acquisition and mergers
			F1-4 Nos. of new rules and regulations coming into place in the year of design	Count of new rules and regulation over the years
F2	Spatial	Network of infrastructure or customers or suppliers distributed in different spatial regions, required memories for process or spaces or resources	F2-1 Owning several design offices in different locations	Nos. of design offices in the year of design development
			F2-2 Diversity of building yards for same design	Nos. of different yards building similar design
			F2-3 Diversity of country of build for similar designs	Nos. of different countries building similar design
			F2-4 Product density	Equipment weight/ L*B*D ratio
F3	Decision-making complexity	Decision points in the design process and the diversity and influential power of different decision makers involved in design development|	F3-1 Domain knowledge of designer	Nos of recorded designs in the segment before the new contract
			F3-2 Customer's financial power	Annual turnover
			F3-3 Customer size	Number of employees
			F3-4 Operational knowledge of customer	Nos. of vessels in the offshore fleet
			F3-5 Potential competitors	Nos. of vessels in similar size and function from other designers
F4	Structural complexity	Intrinsic, measurable degree of complexity driven by number and variety of elements, interrelationships, and dynamics	F 4-1 Vessel size	GT (gross tonnage)* Installed power
			F 4-2 Functional variety	Number of different offshore support functions installed
			F 4-3 Design class size diversity	Main dimension variations inside each design class
			F 4-4 Construction complexity	CGT (compensated gross tonnage)/GT (gross tonnage)
			F 4-5 Brand choice diversity	Nos. of different main equipment brands used to construct similar design
F5	Behavioural complexity	Performance, operations, and reactions to stimuli and the interactions between the elements of the system	F 5-1 Propulsion system diversity	Nos. of different propulsion system types in similar design class (diesel electric, diesel mechanic, hybrid configuration)
			F 5-2 Design class functional diversity	Nos. of different subtypes registered for design class

			F 5-3 Design speed variation	Design speed variation inside each design class
			F 5-4 Installed power variation	Installed power variation inside each design class
			F 5-5 Ice class diversity	Different ice class registered for designs inside design class
F6	Contextual complexity	Environment in which the system operates and corresponding uncertainties	F 6-1 General maritime market situation	Total number of NB contracts in the year of contract
			F 6-2 Segment situation	Total number of NB contracts in the same segment
			F 6-3 Designers general market share	Nos. of sold designs up to the year of contract
			F 6-4 Environmental diversity	Beaufort scale of region/ERN (environmental regulatory number) differences among designs
			F 6-5 Financial status of designer	Design company turn over
F7	Perceptual complexity	Human perceptions and semantics of the design and the problem. Stakeholder preferences, perceptions, and cognitive basis	F 7-1 Customer diversity	Nos. of different customers
			F 7-2 Classification society and rules diversity	Nos. of different class societies selected for designs inside one design class
			F 7-3 Communication simplicity between designer and customer	Local or international customer or both for designs inside one design class
			F 7-4 Communication simplicity between designer and building yard	Local or international building yard or both for designs inside one design class
F8	Temporal complexity	Historical decisions and events and present of system dimensions over the time, time needed for running process	F 8-1 Market trends	Changes in annual contracting activity
			F 8-2 Shipbuilding price changes	New building price index in changes the year of contract
			F 8-3 Global business situation	Business confidence index in the year of contract
			F 8-4 Global economy situation	Global economic growth rate in the year of contract
F9	Technological complexity	Doing something fundamentally new, where technology either must be developed from scratch or embedding new technology in current product	F 9-1 New technologies used	Nos. of patents recorded for the design
			F 9-2 Power plant technological advancement	Diesel electric, diesel mechanic, hybrid or any other advanced type plants
			F 9-3 Redundancy level of dynamic positioning system	DP level (DP1, DP2, DP3) – higher DP redundancy is given higher technological complexity score

SHIP DESIGN COMPETITIVENESS

Definitions and aspects of competitiveness

The evaluation of product competitiveness for companies is one of the key factors for their success in the market. The Oxford Dictionary (2016) defines competitiveness as the ‘Possession of a strong desire to be more successful than others’. In the design domain, competitiveness is often related to notions such as quality, cost, technology advancement, innovations involved in the product, and overall performance (Takei 1985; Gong 2017) . The competitiveness criteria may significantly vary in different sectors or different study situations. Sometimes the same product might need different competitiveness criteria depending upon the market state, competitors’' activities, marketing strategies, or the appearance of new products and actors in the segment (H. Elmaraghy and Elmaraghy 2013). This means that the concept of competitiveness is context-dependent and that its measurement should also reflect and include the competitive environment of the investigated industrial domain. Normally, competitive products are manufactured to sell for profit in specific markets where they can generate maximised results.

Companies use several methods to develop and measure the competitiveness of their products. Ocampo (2017) has introduced an integrated method for estimating the manufacturing competitiveness of companies using their comparative performance in their manufacturing objectives. Using the Delphi method and expert opinion, he identifies cost, environmental protection, delivery time, and flexibility as important competitiveness factors. He defines the general competitiveness measure as a weighted mean of the scores regarding a plant's comparative performance of those factors and related items (Ocampo, Hernández-Matías, and Vizán 2017).

In the maritime industry, it is argued by Cristina (2009) that competitiveness is related to the efficiency and effectiveness aspects of the design solution, construction, and operation of the vessel. Competitiveness in maritime business is a relative term that can be measured in terms of price, unit production cost, labour productivity, fulfilment of customer needs, efficient operation, and higher design performance yield compared to competitors (Cristina et al. 2009). Papanikolaou *et al.*, (2009) relates the competitiveness in the maritime industry with a 'design-for-X' terminology. He sets up a general framework for the design-for-X process, which is defined as the optimisation of a ship with respect to specific important performance indicators and properties, such as design for safety, design for efficiency, design for arctic operations, or design for production. In this approach, when the vessel is designed for a specific objective, the higher the vessel performance on that objective, the higher the competitiveness among the different ship design solutions compared (Papanikolaou et al. 2009).

Measuring competitiveness in ship design

Ulstein and Brett introduced competitiveness as that which makes the vessel design solution more distinctive and the way performance measure analytics support or drive such a distinctive vessel capability to enhance design firm brand. The competitiveness of a ship design solution in their definition is often related directly to the perceived cost–benefit or simply some higher capacities and, in some cases, the functional capabilities of a specific vessel design solution (Ulstein and Brett 2015). Over the years, the Ulstein company has developed its competitiveness measurement model not only from a price or capacity/capability standpoint but in a broader picture, comparing how well the design is balanced from effectiveness, efficiency, and efficacy points of view as competitiveness measures (Ulstein and Brett 2015; Ebrahimi, Brett, and Garcia 2018) (Fig. 1).

Design for effectiveness: the effectiveness of a design solution means doing the right things. How well does the developed ship design solution fit the real and articulated needs of the ship owners. The success of the design solution in the market over previous years is a good indication of the effectiveness of a design solution and design process. The number of sales per design/repeat sales (Szerb and Terjesen 2010; Lei, Yao, and Zhang 2020), the longevity of a design in the market (Haryanto and Moutinho 2017; Ocampo, Hernández-Matías, and Vizán 2017), annual profit per contract (Black and Scholes 1973; Tekce and Dikbas 2009), reputation and awards (Ambastha and Momaya 2005; Wernerfelt and Karnani 1987; Liao 2016), and the annual utilisation of built vessels (ECSA 2017) are the selected items to measure the effectiveness factor in this study. The total number of sales could be directly counted by the number of built vessels for each design class. For example, there are 30 vessels in the market with the design class of B11 (Fig. 5), which means the design is sold 30 times over the years. A higher the number of sales indicates a more competitive design solution in the market. Longevity specifies how a design solution over time is perceived as an old/out-dated design or can still be an attractive solution for new customers. To quantify the longevity of a design solution, the total duration between the first and last contract of a specific design class in the market is taken into account. For example, the A01 design class in our database is sold five times over the years between 2006 to 2013. Hence, the longevity index of the design is calculated as 7. In contrast, although A05 is sold six times, all contracts were made in the years between 2007 and 2008. Therefore, this design is scored 1 in the longevity item.

The financial performance of different designs is measured by the annual profit margin of design companies divided to the total number of sold designs per year. This item is a prominent measure to demonstrate that sustainable competitiveness is not achievable only by the number of sales per design or the longevity in the market, but rather what significantly counts is the created financial margins. Reputation and awards for each design are counted based on the number of global or local awards, such as ship of the year, or global commendations for innovation or an environmentally friendly design. These accolades can enhance the image of the design companies or improve the perceived attractiveness of a design solution in the marketplace. The last item for measuring the effectiveness of a design solution relates to the utilisation of a built vessel over time. Utilisation rate is quantified based on the contractual status of built vessels over the years. Vessels being in operation since their delivery are classified as 100% utilisation, while those vessels which are laid off within the time period are scored lower depending upon the proportion of their idle period.

Design for efficiency: the design for efficiency means doing the right things right. To quantify the efficiency of different design solutions, Ulstein has developed a set of Technical Operational Performance Indexes, which are used in this analysis (Ulstein and Brett, 2015; Garcia *et al.*, 2016; Ebrahimi, Brett and Garcia, 2018). The indexes are developed according to the set of expected functionalities of the vessel design solutions being adjusted as a base for a purpose-built ranking and benchmarking method for offshore service vessels (OSVs). Each individual number is normalised to the average of the total fleet of the relevant segments of vessels to encompass and mitigate the impact of scale differences among different particulars. Competitiveness items relating to the efficiency of a design solution, such as size utilisation (Lee et al. 2014), energy efficiency, environmental friendliness (Turyakira, Venter, and Smith 2014; Flak and Głód 2015; Lei, Yao, and Zhang 2020), and functional/technical performance of the solution (Szerb and Terjesen 2010), are covered in the developed indexing. Vessel performance yield indicators follow a similar idea to that of the EEDI index (Efficient and Operation 2016), which measures the environmental friendliness of vessel designs based on available particulars and capacity data. Eq. 3 depicts the developed power utilisation index (PUI) for anchor handling tug supply (AHTS) vessels. The index shows how efficient vessel-installed power is utilised to cater for needed bollard pull, winch capacity, environmental forces, and vessel speed. Power balancing in the design of AHTSs is a key design task, which is also measured indirectly by this index. Similar indexes also exist for other vessel types based on their core functionalities. Size utilisation, site operation capability index, cargo handling capacity, and general services capability index are examples of such indexing methods.

$$\mathrm{PUI} = \frac{\left(\frac{Bollard\ Pull}{74}\right) \times \left(\frac{Winch\ Pull}{143}\right) \times \left(\frac{Sea\ State}{5{,}4}\right) \times \left(\frac{Speed}{12{,}2}\right)}{\left(\frac{Power}{4177}\right)} \tag{3}$$

Efficacy The efficacy aspect of competitiveness means using the right resources to do the right things right. To address the use of the right resources in the design phase, three items of total profit per employee, total number of contracts per employee, and different vessel segments covered by each employee in the year of the design contract are selected. The expertise and domain knowledge of designers and their efficiency in the design development process (Szerb and Terjesen 2010; Španja, Krajnović, and Bosna 2017; Stavropoulos, Wall, and Xu 2018) are covered through these items. To use the right ship design tools in the design process is another item covered in this factor.

The summary of the factors and items to quantify ship design competitiveness in this study is presented in Table 2. The competitiveness items are the result of literature review. The item categorisation for each factor was the result of expert judgment at Ulstein. Each item is measured based on real data of design solutions and design firms. In the succeeding step, real calculated values are converted to scale measures between 1 to 5 based on the distribution of the real data. Each competitiveness factor is the total sum of its relating items. Similar weights are assigned to all three factors, and competitiveness is calculated as the sum of the effectiveness, efficiency, and efficacy scores. To avoid scale effect, the factors are normalised before final aggregation.

Table 2: The three competitiveness factors and relevant items

	Factors	Explanation	Items
F1	**Design for effectiveness**	Doing the right thing - this aspect reflects the appropriateness of the design decisions. How right have been the design decision and up to which extent the design solution has been successful in the market over the years	F1-1 Number of sales for each design over the years
			F1-2 Longevity of the design over the years
			F1-3 Annual profit per design contract
			F1-4 Reputations / Awards
			F1-5 Annual utilization of a built vessel
F2	**Design for efficiency**	Doing the right thing right - this factor reflects how efficient is the developed solution. Different indexes are used for measuring this factor	F2-1 Power utilization Index
			F2-2 Size utilization index
			F2-3 Site operation efficiency index
			F2-4 Energy efficiency index
			F2-5 Vessel general service index
F3	**Design for efficacy**	Doing the right thing right with right resources - this factor presents how well resources are utilized to develop design solutions over the years	F3-1 Annual profit/employee
			F3-2 Total number of contract/Employee in different years
			F3-3 Different vessel segments covered by employees in different years

DATA ANALYSIS AND RESEARCH RESULTS

This section explains both the exploratory and confirmatory steps of our data analysis. In the exploratory analysis, which is the first part of this study's data analysis process, appropriate insights into the available archival data are developed. In this phase, we establish a structured, comprehensive dataset, where the data have been presented and manipulated in such a way as to draw out important necessary insights. In the confirmatory phase, observations and evidence using traditional statistical tools, such as significance, power of analysis, and confidence level, have been evaluated. By running the confirmatory analysis, any existence of deviation from the developed investigative model in the results of the data analysis is examined. Testing hypotheses, performing a regression analysis of the theorisation model, conducting an analysis of variance, and investigating the level of correlation between complexity and competitiveness are all part of the research's confirmatory analysis.

Statistical characteristics of the developed vessel database

For the selection of the sample data, we have mainly used the registered vessel information available in the 'World Register of Ships' and the Ulstein vessel segment databases (IHS Fairplay, 2020)("Ulstein Segment Vessel Data Basis-Inhouse Vessel Data Base" 2020) as well as enterprise information webpages, including Proff.no (Finder, 2020), Bloomberg.com (Bloomberg, 2020), and (Linkedin.com) (*Linkedin webpage*, 2020). Other relevant supplementary public information, available on the Internet, about different vessel particulars and the websites of different ship design and ship owning companies are also used in the data collection and analysis.

Offshore support vessel designs developed after 2000 from eight major Norwegian ship designers (designers A–H to maintain anonymity) were selected for this study. Based on the available statistics, almost 26% (687 vessels out of 2622 registered vessels) of the offshore vessels contracted after 2000 with a size larger than 2000 tonnes deadweight tonnage (DWT) were designed by selected Norwegian designers, including Ulstein. Among the different vessel types in the sample, 48% were platform supply vessels (PSVs), 26% were AHTS, and the remaining 26% were offshore vessels. The selection of 687 vessels represents 134 different design classes, which are sold to more than 190 different ship owners. By reviewing the availability, reliability, and robustness of the data in the dataset, 34 designs were excluded and the remaining designs selected for the rest of the analysis. The remaining dataset contains 100 different designs representing 492 offshore vessels. This means that almost 74% of the design solutions as well as 76% of the contracted vessels from the original database are already covered in the new database for the rest of the analysis. This, however, meets the minimum recommended level of 5:1 observations for statistical analysis with respect to the number of independent variables (Hair et al. 2010). Still, the generalisation of the results can be questionable due to the focus of the study on Norwegian designers and a set of specific vessel types.

The final dataset contained 492 vessels built based on 100 different designs and being sold to 123 different ship owners. Fig. 2 presents the number of vessels designed by each designer and the type of vessels in the final database. As illustrated in the figure, 24% of the vessels in the final database are designed by Designer A, while Designer B holds 22% of the share. Designers C, D, and E are in the next places, respectively, by 15%, 14%, and 13% of the designed vessels in the dataset. To conduct the research analysis, the final database was randomly divided into two – small and large samples. The small sample was utilised as a test case for quick analysis. The sample included 25 designs (25% of the dataset). The combination of 51 construction vessels, 23 PSVs, and 22 AHTSs represented the 96 vessels and 25 designs of the small sample. The remaining 75% of the designs were used in the large sample for the main analysis. Quick sampling was used to test the investigation model and to find any need for modification or changes in the data gathering methods, add or reduce the items, or update the factors or constructs. Based on the findings and observations from the quick sampling, the final analysis was conducted on the large sample. The large sample of this study included 75 designs representing 396 offshore vessels of the following types: 104 OCVs, 72 AHTSs, and 222 PSVs. Collected OCV vessel data included different subtypes of pipe layer vessel (PLV), dive support vessel (DSV), heavy lift vessel (HLV) as well as inspection, maintenance and repair (IMR) vessel.

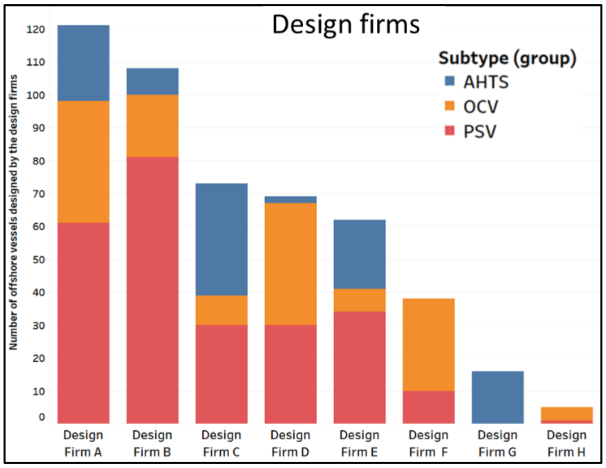

Figure 2: The number and type of the vessels designed by each designer

Different designs were grouped based on their design family in the final database. For example, for Design firm A, we identified 36 design classes in the database, as Fig. 3 shows. For example, design class A 18/1 and A 18/2 or A 26/1, A 26/2, A 26,3 are combined in the final data base as presented. Such combination is implied to other design classes with similar design names. Various subtypes under each design class is also distinguished by different colours in the figure.

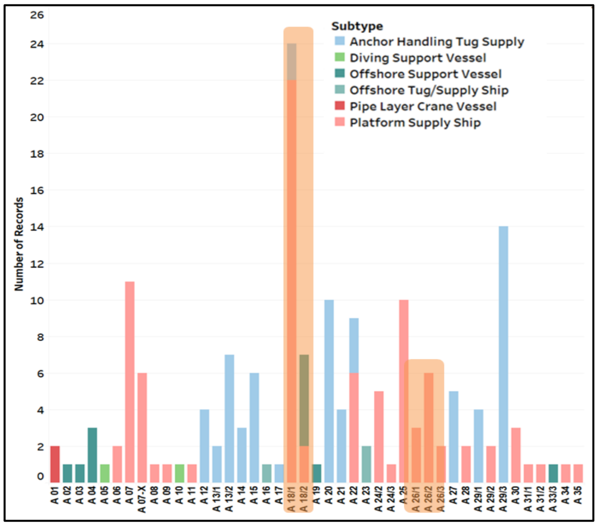

Figure 3: Different design classes and their vessel types developed by Designer B

Examination of data

Before running the final CCA and MLR analysis of the complexity and competitiveness factors, we examined whether the following assumptions were satisfied: the independence of the observations, the linear relationship between the dependent variable and each of the independent variables, data homoscedasticity, noncollinearity or multicollinearity, and normality of data distributions. A summary of the descriptive statistic functions for both the dependent and independent variables was preliminarily calculated. These descriptive statistics included mean, median, variance, standard deviation, and minimum and maximum (Table 3).

Table 3: Descriptive statistics of the data.

	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic
Effectivenes	13,0	6,0	19,0	12,2	2,4	5,7
Efficiency	13,5	8,4	21,9	14,5	2,7	7,4
Efficacy	15,4	4,6	20,0	11,9	4,6	20,9
Directional	13,8	6,3	20,0	13,4	2,7	7,3
Spatial	15,0	5,3	20,3	12,7	3,2	9,9
Decision making	13,0	6,9	19,8	12,1	3,0	8,8
Structural	11,8	8,3	20,0	13,1	2,6	7,0
S.Behavioural	13,0	7,0	20,0	9,8	3,2	10,2
Contextual	12,8	7,2	20,0	12,7	2,9	8,5
Perceptual	14,1	5,9	20,0	10,1	4,0	15,8
Temporal	13,8	6,3	20,0	13,1	4,0	15,9
Technological	11,5	8,6	20,1	15,3	2,4	5,9

Further, we have run the normality test based on both the Kolmogorov-Smirnov and the Shapiro-Wilk tests (Ghasemi and Zahediasl 2012). Visual inspection of the data distribution and residual curve was also acceptable as an alternative method for a normality check (Hair et al. 2010). Based on our sample size, if the statistic value (z) exceeds the values -1.96 or 1.96, or if the significance level (p) is below .050, the hypothesis of normality is rejected (Pituch and Stevens 2016). Table 4 includes an overview of the skewness, kurtosis, statistic values (z), and significance levels (p) for all variables studied based on both methods. None of the factors or constructs exhibits a statistically significant departure from normality in terms of statistic value (z), however, they do in terms of their significance (p). Considering the significance levels (p), the following three factors differ from normality based on the Shapiro-Wilk test: temporal, technological, and efficacy. A possible way to fix the normality issue is to apply a transformation function (Hair et al. 2010; Pituch and Stevens 2016). Due to the shape of distributions, the logarithmic function of $x_j' = \log x_j$ was selected for normalisation of the data. The new significant values of transformed data were also included in the table. Still the p-values are slightly lower than 0.05. Therefore, the normality of these factors by means of graphical representation were evaluated and accepted. A regression standardised residual plot and residual scatter plot of the analysis have also confirmed the normality of variables.

Table 4: Data normality test

	Skewness	Kurtosis	Kolmogorov-Smirnov		Shapiro-Wilk	
	Statistic	Statistic	Statistic	Sig.	Statistic	Sig.
Dependent variables						
Effectiveness	0,771	1,246	0,176	0	0,93	0,045
Efficiency	0,3	0,513	0,094	0,098	0,974	0,117
Efficacy	0,043	-0,801	0,125	0,006	0,934	0,001
Independent Variables						
Directional	-0,136	0,858	0,16	0	0,912	0.001- (0,021)
Spatial	0,444	0,314	0,099	0,065	0,973	0,11
Decision-making (DM)	0,684	0,131	0,091	,200*	0,981	0,316
Structural	0,489	-0,021	0,105	0,038	0,973	0,103
Behavioural	1,221	0,728	0,083	,200*	0,972	0,092
Contextual	0,509	0,173	0,097	0,078	0,98	0,28
Perceptual	0,665	-0,401	0,076	,200*	0,983	0,41
Temporal	0,581	-1,216	0,177	0	0,917	0.000- (0,03)
Technological	-0,288	0,507	0,302	0	0,758	0.00 –(0,0015)

*. This is a lower bound of the true significance.

Fig. 4 shows the visual distribution of the transformed data for directional complexity.

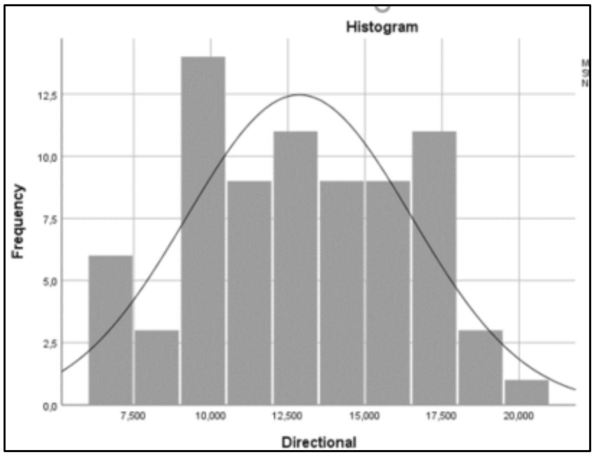

Figure 4: Visual normality test of directional complexity factor

Homoscedasticity refers to the assumption that dependent variables exhibit equal levels of variance across the range of a predictor variable. From a visual inspection of the standardised residuals against the predicted dependent variable in Fig. 5, no major deviations were perceived on the variance of error along with the values for the dependent variable. Thus, the data reflected homoscedasticity, and the standard errors were not biased. In such circumstances, conducting significance tests and confidence intervals will not lead to incorrect conclusions about the significance of the regression coefficients (Pituch and Stevens 2016).

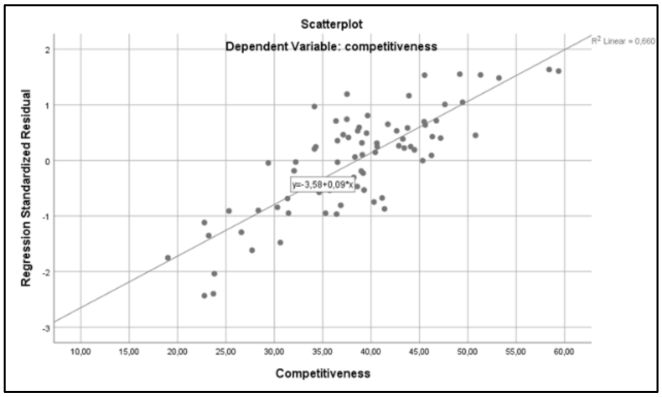

Figure 5: Homoscedasticity–heteroscedasticity test

A multicollinearity test was also carried out to study the relationship between more than two independent variables. Variance important factors (VIF) lower than 3 and with a tolerance above 0,1 are the two factors the literature suggest for multicollinearity testing (Yoo et al. 2014; Hair et al. 2010). The estimated VIF for the independent variables of our study were in the range of 1,116 to 1,871, and the tolerances ranged from 0,535 to 0,896. Both tolerance and VIF values are inside the thresholds indicated by the literature, suggesting that collinearity and multicollinearity do not present any problems in this research.

Canonical analysis CCA

The result of the CCA is presented in Table 5. Three canonical roots were identified within the analysis. Based on the results from the first root, the full model is statistically significant, with a Wilks's λ of 0.279 and p < .001. The defined limit of 0,05 for p-value (level of significance) in this analysis is the probability of rejecting the null hypothesis when it is true (Pituch and Stevens 2016). Based on the result of analysis, we can reject the null hypothesis that states 'there is no relationship between the independent and dependent variable sets' (i.e. reject H0) and conclude that there is a strong relationship between complexity and competitiveness. The magnitude of the relationship for root 1 is measured by squared canonical correlation as 52%, respectively.

Table 5: Result of canonical analysis

	Canon Cor.	Sq. Cor	Wilks Statistic	Sig.
Root 1	0,719	0,51662	0,279	0,000
Root 2	0,558	0,31136	0,577	0,002
Root 3	0,403	0,16273	0,837	0,101

MLR analysis

The model summary of the confirmatory analysis for both the large sample and the convenience sampling study is presented in Table 5. The power of analysis (Sig. F) complies significantly with our findings from the canonical correlation. The result shows a strong relationship between ship design complexity and ship design competitiveness. In the small sample (due to the sample size), the Sig. F value is higher than 0.05, while in the large sample the issue is resolved. The coefficient of determination R2 is calculated to be 0.340 and 0.550 for both samples, respectively. Our canonical study explains more of the competitiveness by complexity in root1 with 51% squared R, where efficacy has only a trivial influence on the synthetic canonical criterion. In our MLR model, the produced competitiveness index is the total sum of effectiveness, efficiency, and efficacy with equal weights. If we remove efficacy from our competitiveness index in the MLR model and re-execute the analysis, the results are improved considerably, resulting in an R-square of .490 and, adjusted, R is .420, respectively, which are more compatible with the results from the first canonical function (root) of the CCA. The reason for less influence of efficacy factor in our analysis can be explained by the nature of our gathered data. The items constituting efficacy factor in our model reflects human resource competence related aspects including annual profit per employee, total contract per employee and number of vessel segments per employee. Since study period is limited to Norwegian ship designers and offshore vessel segment such findings can be expectable. According to our experience, typically the level of competences among the designers in various design firms in Norway is not that different. Therefore the influence of this factor seems to be inconsiderable in our model compared to effectiveness and efficiency factors. The results can be further validated in future researches by adding data from non-Norwegian design firms in the data base and reconducting the analysis.

Table 6: MLR results summary for both samples

Model Summary^b					
Model	N	R	R Square	Adjusted R Square	Change Statistics
					Sig. F Change
Large sample	75	0,583^a	0,34	0,249	0,001
Small sample	25	0,742^a	0,55	0,281	0,107
a. Predictors: (Constant), Technological, S. Behavioural, DM, Temporal, Directional, Spatial, Contextual, Structural, Perceptual					
b. Dependent Variable: Competitiveness					

Table 7 includes the results from the multivariate regression analysis of our research model from Fig. 3. The regression coefficients b and Beta (columns one and three of Table 7, respectively) reflect the change in the dependent variable for each unit change in the nine independent factors. Exploring the standardised Beta coefficient, the independent variable *spatial* has the largest positive contribution to competitiveness. Furthermore, the *temporal* and *decision-making* factors have negative contributions to the dependent variable ship design competitiveness. The results show that the influence of technological complexity is trivial and nearly negligible. These results and findings are discussed in the next paragraphs of this article.

Table 7: Results from the regression model by confirmatory analysis

Indipendent factors	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	53,718	11,834		4,539	0,000
Directional	-0,543	0,338	-0,179	-1,608	0,113
Spatial	0,735	0,302	0,282	2,434	0,018
Decision making	-0,770	0,313	-0,278	-2,459	0,017
Structural	0,454	0,370	0,147	1,229	0,224
S.Behavioural	-0,459	0,354	-0,179	-1,297	0,199
Contextual	-0,440	0,336	-0,157	-1,308	0,195
Perceptual	0,455	0,273	0,221	1,667	0,100
Temporal	-0,678	0,219	-0,329	-3,091	0,003
Technological	0,036	0,398	0,011	0,090	0,928

FINDINGS AND INTERPRETATION OF THE RESULTS

The results of this study reject the null hypothesis and confirm that there is a strong relationship between ship design complexity and ship design competitiveness. The findings from the MLR analysis suggest that the presence of ship design complexity can explain 34% of the variability in ship design competitiveness. The final structural model and the influence of each complexity factor on ship design competitiveness is presented in Fig. 6. Four of the factors – *Spatial, structural*, *perceptual* and *technological* – have a positive βeta value, indicating that one unit change in the factor will produce a positive change in the competitiveness of magnitude βeta. Alternatively, the factors *directional, decision-making, behavioural, contextual,* and *temporal* have a negative βeta value. These findings do not entirely comply with our alternative hypothesis, which suggested that all nine factors have a negative influence on ship design competitiveness.

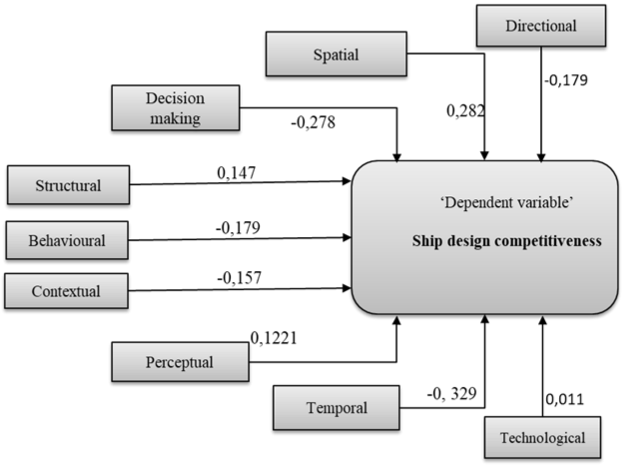

Figure 6: Loadings of independent factors on dependent construct (β-values from Table 7*)*

Among the factors with a positive influence on competitiveness, *spatial complexity* is the one with the highest contribution. This means that designers who have had different design offices worldwide in the period of study have shown a higher level of competitiveness in the market. The experiences from the Ulstein offices in China, Singapore, Brazil, Turkey, and Poland well comply with such observations. Employing local people to better access the local market, handle the cultural differences with customers, and make better relationships with authorities and local shipyards to build the designs in different countries has had a positive impact on ship design competitiveness over the years. Although extra costs and complexities have been associated with such enlarging of the design environment for Ulstein, it has improved our international sales. Almost 70 % of Ulstein design sales in the years between 2005 to 2015 has happened through offices in other countries and vessels were built-in third-party yard than Ulstein yard in Norway. Similar situation is observed for other Norwegian design firms with distributed design offices. Moreover, the capability of ship design companies to collaborate with different shipyards worldwide is also a great advantage, positively influencing the competitiveness of the design solutions.

Together with spatial complexity, the factor *structural complexity* also has a positive contribution to ship design competitiveness. This finding is supported by some researchers but in contradiction with the arguments of others (Maurer 2017; Maurer, Maik 2007; Lindemann, Maurer, and Braun 2009; W. Elmaraghy et al. 2012). Our experiences at Ulstein also comply with this finding. It has been proven over time that Norwegian designers are not that competitive in the design small PSVs (smaller than 2000 tonnes DWT) or AHTSs (less than 150 tonnes bollard pull) as the market is populated with low-cost Asian designers. The financial results and the level of market share of different design firms shows European ship design and construction firms, most specifically the design firms of this study are more competitive in the global market in the design/construction of complex products such as complex offshore vessels or cruise ships. Despite there being no competitive advantage for Ulstein to enter into the design/construction of simplistic general cargo vessel types where east Asian firms are more competitive to produce less expensive product. The main competitive advantage of Norwegian shipyards over the years has been the construction of more complex, equipment/outfitting intensive service vessels, and Asian yards are more competitive with steel-intensive cargo vessels.

Perceptual complexity and *technological complexity* are the two remaining complexity factors with a positive influence on ship design competitiveness. The results show that design companies that have been able to handle the communication issue of dealing with a wide range of customers have achieved higher ship design competitiveness. Being able to deal with different classes of societies and to build in both local and international yards have helped the designers to enhance their competitiveness.

Among the nine defined complexity factors, *technological complexity* surprisingly has the lowest statistical significance and magnitude in regard to a positive influence on competitiveness. A similar level of applied technologies among almost 80% of the vessels in the sample or the high cost of employing advanced technologies in the maritime industry can be the reasons for such a finding.

Not surprisingly, *temporal complexity* and *decision-making complexity* are the factors with the highest negative influences on ship design competitiveness. When the market faces economic crisis and extreme volatilities, such as what happened in 2008 and its following economic downturn from 2009, it defaults on making profits, and serving debt is deteriorated quickly. Consequently, the performance yield of vessel design firms has seen their accounts' top-lines and bottom-lines drastically shrink. This situation may lead to bankruptcies or a lack of adequate financial funding/support – unavailable lending opportunities and drastically depreciated competitiveness (Brett et al. 2018). Alternatively, as a consequence of a high level of decision-making complexity, it has been experienced at Ulstein entering into, for example, the cruise exploration vessel segment after almost 16 years of focused design and production activity of offshore vessels , has been much more challenging and resource demanding than what was expected. Although some experiences in the design of marine platforms and related main systems were transferred to the new segment, massive differences were also realised. Wider possible solution spaces in terms of luxury level, space arrangement issues in hotel function, different rule and regulation regimes, a segment more sensitive to stability criteria and lightweight, and a greater necessity for better seakeeping performance and comfort criteria were some of the main experienced discrepancies. In addition to these technical and operational differences, dealing with more professional customers and entering into new market domains with their particular characteristics were some of the commercial issues. Lack of enough know-how and experiences in these new domains enforced Ulstein to use at least double the time and resources to develop the first cruise exploration concepts compared to the design of similar-sized offshore vessels. The same issues happened in the vessel cost/price and construction time estimations in early design phases, which eventually led to lower margins and even losses in some cases because of such increased decision-making complexity.

Behavioural and *directional complexity* factors have negative consequences on competitiveness, with a beta value of -0.179. Our experiences at Ulstein show that in order to sell more of an existing design to a new customer typically requires making changes in vessel design speed, ice-class notation, vessel operability, hotel size/luxury level, mission equipment, and/or even bow and aft shapes. These modifications are most often associated with extra analysis and even, in many cases, new model tests in the early design phase to compensate for emerging behavioural uncertainty/complexity. Such extra design and construction costs might be the reason for lower competitiveness compared to more standardised design classes. Moreover, the findings of this analysis also support the literature addressing the issue of directional complexity. The results depict those companies with more stable management over time, less major changes in organisation, and clearer goals and objectives as well as appropriate integration in the target society have been more competitive by selling more designs and making more profit over the time period. Moreover, the results indicate that more competitive design classes were developed when the design organisations have been smaller in size and more flexible in their operations. The last factor with a negative influence is *contextual complexity*. Critical financial situations or the low turnover of a design company, in addition to inferior market share and reputation in the segment compared to competitors, can negatively influence competitiveness. Ship design competitiveness is also negatively influenced when the total number of worldwide new-building contracts is low.

SUMMARY AND CONCLUSION

In this paper, we have critically reviewed and elaborated in both quantitative and qualitative ways as to whether there is any relationship between ship design complexity and ship design competitiveness. After reviewing the literature, we propose that there is no universal consensus on the influence of ship design complexity on competitiveness and that different researchers have addressed the issue from different perspectives. Very few have taken a broader approach to the issue at hand. In this article, we have approached complexity in ship design according to nine factors of directional, spatial, decision-making, structural, behavioural, contextual, perceptual, temporal, and technological. A comprehensive method to quantify ship design complexity based on items constituting each factor is applied in this research. Ship design competitiveness was explored and measured by means of the following three design perspectives: design for effectiveness, design for efficiency, and design for efficacy and their constituting items.

In this paper, we have collected archival data of 492 vessels built based on 100 different design classes and being sold to 123 different ship owners. The designs were developed by eight major Norwegian designers after 2000. We conducted the analysis in two steps, with a small and a large sample, which were randomly selected from the original dataset. The small sample included 25 designs (25% of the dataset), demonstrating 96 vessels in the market. The combination of 51 construction vessels, 23 PSVs, and 22 AHTSs represents the 96 vessels of the small sample. The remaining 75% of the designs were used in the large sample for the main analysis of this research work. The large sample of this study embraces 75 designs representing 396 offshore vessels of 104 OCVs, 72 AHTSs, and 222 PSVs. Multivariate data analysis techniques, including multiple regression and canonical analyses, were selected and used to analyse the extracted archival data.

The result of this study shows that there is a strong correlation between ship design complexity and ship design competitiveness. The research results suggest that the presence of complexity in ship design can explain 34% of the variability in ship design competitiveness. Four of the factors – spatial, structural, perceptual, and technological – have a positive influence, indicating that one-unit change in the factor will produce a positive change in competitiveness. The factors of directional, decision-making, behavioural, contextual, and temporal have a negative influence. These findings are not entirely compatible with our set of propositions and alternative hypothesis, which suggested that all nine factors have a negative influence on ship design competitiveness. Our results show that the independent variable *spatial* has the largest positive contribution to ship design competitiveness, while the *temporal* and *decision-making* factors have the highest negative contribution to the dependent variable. It is also concluded that the influence of technological complexity is trivial and nearly negligible, which was far from our initial expectations.

According to our findings, nine independent complexity factors and their associated items contribute – to different degrees – to ship design competitiveness. Despite the differences in the perception of how the diverse ship design factors contribute to ship design competitiveness, ship designers do not seem to put a great deal of emphasis and effort into them. The result of this article can help ship designers concentrate their efforts on those factors perceived as more important and put less emphasis on those with lower relevance.

This empirical analysis has focused only on a specific vessel segment developed by Norwegian designers. Changes in vessel segment or expanding the analysis to designers of other regions might influence the results. Therefore, the generalisation of the results herein is limited until further studies can cover a wider range of vessel types and more geographically diverse designers.

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