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Jose Jorge Garcia Agis

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Doctoral Thesis

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Thesis for the degree of Philosophiae Doctor

Trondheim, February 2020

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Abstract

The objective of this thesis is to develop a better understanding of how to carry out more effective conceptual ship design processes. Under the premise that uncertainty influences the effectiveness of the decision-making process in ship design, it is argued that to improve the way daily ship design activities are carried out, it is necessary to understand the uncertainty present in such processes. It is also necessary for ship designers to know how to reduce the negative effects of uncertainty. This research tries to find answers to the following research questions: *What are the important uncertainties in conceptual ship design, and how do they influence effective decision-making?*

The research question is explored using a multi/mixed-method denominated exploratory design research. It consists of exploring a phenomenon based on a qualitative evaluation and then probing quantitatively the extracted hypothesis. The initial analysis requires a deep evaluation of uncertainties in the ship design domain as perceived by the different actors involved in the conceptual design phase of new ships. Particular attention is given to the role of the ship owner in the design process. An extensive literature review is carried out to explore the role of uncertainty in ship design decision-making. An investigative model is developed based on this literature study. Further, our developed investigative model is tested using multivariate regression analysis. The data analysed was collected through an online survey involving 23 shipping companies.

This research has confirmed a relationship between the independent and dependent constructs *uncertainty* and *decision-making effectiveness. Uncertainty* is found to explain 14% of the variability of *decision-making effectiveness* in conceptual ship design processes. Furthermore, *uncertainty* is also confirmed to consist of five factors: (i) *context*, (ii) *agent*, (iii) *input*, (iv) *model* and (v) *process*. These factors contribute differently to the *decision-making effectiveness*. The independent factors *context*, *agent* and *model* have a positive effect on *decision-making effectiveness*, meaning that the higher the emphasis given to these factors in the design process, the higher the *decision-making effectiveness* of the design process. The independent factor c*ontext* has the most significant effect (19.5%), followed by the independent factors *agent* (19.0%) and *model* (15.9%), respectively. The independent factors p*rocess* (-30.9%) and *input* (-19.7%) have been found to have, surprisingly, a negative effect on the effectiveness of the conceptual design process, meaning, and contrary to literature findings, the higher the emphasis given to these factors during the design process, the lower the effectiveness of the ship design process.

Among the 43 items describing the five factors of uncertainty, regulations (*context* uncertainty) were perceived by shipping companies as the most critical factor. This is likely due to the ongoing environmental regulatory transformation, in particular, the IMO (International Maritime Organization) 2020 emission requirements. The experience of the stakeholders involved in the newbuilding project (*agent* uncertainty) is perceived as the second most influential item in terms of importance to the overall perception of uncertainty. For example,

market studies are a useful tool for shipowners and designers to select experienced partners or suppliers in their future projects. The third most important item is the economic performance of the vessel design (*context* uncertainty). This item reflects the lack of information relating to the potential revenue making capability of the vessel and the associated costs of owning and operating it. Vessel economics has, therefore, been introduced at Ulstein as an essential tool for supporting the conceptual design process and reduce uncertainty relating to the economic performance of the vessel.

The most important result from this study is the categorization of uncertainty in ship design and the quantification of the relationship between the perception of uncertainty from the perspective of the ship owner and the effectiveness of the conceptual ship design process. Furthermore, we exemplify the applicability of uncertainty handling methodologies to reduce the uncertainty or to mitigate the negative effects of uncertainty in five user-cases. This research provides a list of uncertainty factors (as perceived by ship owners) that ship designers should be aware of (and do something about) in their daily activities to improve the effectiveness of the ship design process.

"ignorance more frequently begets confidence than does knowledge"
(Darwin, 1871, p. 3)

«A Man with a watch knows what time is it, a man with two watches is never sure” (Stephen Stigler, 1987)

Preface

This thesis is submitted for the partial fulfilment of the requirements for the Degree of Doctor of Philosophy (PhD) in Marine Technology at the Norwegian University of Science and Technology (NTNU).

The work was carried out between January 2016 and October 2019 primarily at two locations. During the calendar years 2016, 2018 and 2019 I, was located at Ulstein International AS at its facilities in Ulsteinvik, Norway. During the calendar year 2017, I was located at the Department of Marine Technology at NTNU in Trondheim, Norway. Additionally, during the summer 2016 and spring 2017, I visited the Systems Engineering Advancement Research Initiative at MIT, Boston, for three short research stays. The research work was supervised by Professor Stein Ove Erikstad from NTNU and co-supervised by Deputy Managing Director and Professor II Per Olaf Brett from Ulstein International AS and NTNU.

The research was funded by Ulstein International AS and The Norwegian Research Council through an industrial PhD scheme.

The target audience for this research is academics and seasoned practitioners with interest in ship design, decision-making and handling uncertainty in such critical work process.

Acknowledgement

This research has been carried out as a collaboration between Ulstein International AS (UIN), a fully subsidiary of Ulstein Group ASA, and the Department of Marine Technology on the Norwegian University of Science and Technology in Trondheim. This collaboration wouldn't be possible without the close collaboration between the two institutions and the people working in them.

The foundations of this research were laid down in 2013 when I moved to Norway as an exchange student. Under the supervision of Prof. Stein Ove Erikstad, I carried out my MSc thesis on the conceptual design of a cable laying vessel for operation in the growing offshore wind market. When I finalize the thesis and consequently the MSc degree, I had the opportunity of joining Ulstein International AS in August 2014 as a business analyst under the supervision of Deputy Managing Director Dr. Per Olaf Brett. After one and a half years working at UIN, the opportunity of a deeper study of ship design became effective as part of an industrial PhD program partially funded by The Research Council of Norway (NFR).

This research work wouldn't be possible without the trust and support of my two supervisors, Prof. Stein Ove Erikstad and Prof. II Per Olaf Brett. I also appreciate the contributions of Prof. Bjørn Egil Asbjørnslett. This research work wouldn't be possible without the close collaboration with my fellow PhD students Ali Ebrahimi, Sigurd Solheim Pettersen and Carl Fredrik Rehn.

I wish to thank my colleagues at the different business areas of the Ulstein Group, both in Norway, Netherlands and China, and specially Ulstein International AS; our daily and weekly discussions have strengthened the findings from this research.

I also thank my fellow PhD students at the Department of Marin Technology (IMT), thank you for integrating me during my one year stay there. To Dr. Donna Rhodes and Dr. Adam Ross from the Systems Engineering Advancement Research Initiative, MIT, Boston. Thank you for your kind invitation to your facilities at the Massachusetts Institute of Technology (MIT) and for your valuable contributions and discussions during my stay there.

Finally, I would like to acknowledge the role of my family in this research work. You have always been there for me when I needed you. This wouldn't be possible without the continual support and trust of my parents Jose and Angela. The abilities and principles you have taught me during my infancy and adolescence have been essential in this research journey. To my sister Angela, I thank for being a good example to follow and guidance during my earlier studies. Special recognition to my niece Alejandra, who came to life halfway in this research period, thank you for bringing light and energy in the finalization of this research.

Contents

List of Tables

List of Figures

Definitions

Uncertainty

State reflecting the lack, inaccuracy or deficiency of information. Any situation outside pure certainty, independently of the degree of uncertainty.

Conceptual ship design

The first stage of a ship design process. This process is commonly referred to as to *feasibility study, concept design* or *preliminary design*. In this thesis, conceptual ship design reflects all the activities taking place before a newbuilding contract is signed.

Effectiveness

The degree to which something is successful in producing the desired result. In ship design, effectiveness represents *how well* a vessel design solution fulfils its initial goals. It captures the level of satisfaction of decision-makers (a particular stakeholder or a mutually agreeable among all the stakeholders) as regards to the objectives and expectations set.

Holistic ship design

An approach to ship design considering commercial, operational and technical aspects of the ship design and its life cycle.

List of abbreviations

ABD	Accelerated Business Development	MDP	Markov Decision Process
AHTS	Anchor Handling Tug Supply	MOE	Measure of Effectiveness
AI	Artificial Intelligence	MOP	Measure of Performance
AUT	Anticipated utility theory	NOK	Norwegian Kroner
CAPEX	Capital Expenses	NOx	Nitrogen Oxides
CFD	Computerised Fluid Dynamics	OCV	Offshore Construction Vessel
CoA	Contract of Affreightment	OO&G	Offshore Oil & Gas
CtO	Configured to Order	OPEX	Operational Expenses
DBD	Decision-Based Design	OSV	Offshore Support Vessel
DDM	Dynamic Decision Making	PEST	Political, Economic, Social, and Technology
DFC	Design for Changeability	PDM	Product Data Management
DME	Decision-Making Effectiveness	PL&C	Physically Large & Complex
DMM	Domain Mapping Matrix	PLM	Product Lifecycle Management
DP	Dynamic Positioning	PSV	Platform Supply Vessel
DSM	Dependence Structure Matrix	RA	Research Activity
DW	Durbin-Watson Test	R&D	Research & Development
DWT	Deadweight	RL	Reinforcement Learning
EPM	Enterprise Performance Management	RO	Research Objective
EPU	Economic Policy Uncertainty	RPD	Recognition-Primed Decision
ERM	Enterprise Risk Management	RQ	Research Question
EtO	Engineering to Order	RSC	Responsive Systems Comparison
EUT	Expected Utility Theory	ROI	Return on Investment
FEED	Front-End Engineering Design	SA	Supporting Article
FR	Functional Requirement	SC-MDP	Ship-Centric Markov Decision Process
GA	General Arrangement	SE	State Estimator
GDP	Gross Domestic Product	SEUT	Subjective expected utility theory
GEPU	Global Economic Policy Uncertainty	SOx	Sulphur Oxides
GT	Gross Tonnage	SR	Success Rate
IMO	International Maritime Organization	StO	Standardized to Order
ISO	International Organization for Standardization	SWOT	Strengths, Weaknesses, Opportunities, and Threats
LCOE	Levelized Cost of Energy	TELOS	Technical, Economic, Legal, Operational, and Schedule
LNG	Liquified Natural Gas	UAI	Uncertainty Avoidance Index
LOA	Length Over All	UGPI	Ulstein General Performance Index
M&S	Modelling & Simulation	VIF	Variance Important Factors
MA	Main Article	VOI	Value of Information
MAE	Multi Attribute Expense	VOYEX	Voyage Expenses
MAUT	Multi-Attribute Utility	VUCA	Volatility, Uncertainty, Complexity, and Ambiguity
MAUT	Multi-Attribute Utility Theory	WUI	World Uncertainty Index

1. Introduction

Ulstein Group ASA is the parent company of a group of maritime companies, specialising in ship design and maritime solutions, shipbuilding, power and control, equipment manufacture and system integration and shipping. We at Ulstein have historically worked with vessels in the offshore oil & gas industry, and more recently with passenger vessels, including exploration-cruise and RoPax, service vessels, heavy lift installation vessels and cable layers for the offshore wind energy generation market, and finally factory stern trawlers. To design and build vessels are challenging activities. For companies like Ulstein, who focuses on complex and innovative designs this situation is apparent. Our daily activities of designing and building vessels normally, require solving problems that haven't been solved before and always searching for vessel solutions that increase the effectiveness of their predecessors.

In the past, the design process of a new vessel at Ulstein used to start by identifying a set of needs and expectations from the shipowner. In most cases, this information was received in the form of a tender or specification document, sometimes only as a summary in a scratch book based on a telephone call. This tender document or specification typically consisted of one to five pages describing the initial expectations of the customer in the form of technical requirements: length, beam, cargo capacity, speed, etc. Building on this set of requirements we would have proposed an initial hull, calculated its resistance, started drafting the general arrangement, weight estimates, stability and so on. This process typically required two to three iterations before the design was properly balanced. After this process, which may have taken three to five weeks, we were ready to present the concept vessel design solution to the customer. Yet, through that design process, we had made a multitude of assumptions in many cases resulting from lack of information. These assumptions include factors such as the commercial operation of the vessel, its operational profile, operational speed, or the ability of the crew to operate the vessel. If these assumptions were correct and accepted by the shipowner, the project would proceed and be further developed into a basic design and finally priced at one or more yards. On the other hand, if the assumptions were not correct or were not accepted by the shipowner, the existing design had to be adjusted or, in some cases, started from scratch.

It is the proposition of this research work that such unnecessary, time-consuming and costly situations appear as a consequence of not being able to handle apparent and hidden uncertainties. The assumptions and ignorance of uncertainty in the traditional way we have been carrying out the ship design process in the past could easily lead to ineffective and inferior work processes, requiring substantial resources for adjustments and rework. Such effects of uncertainty did appear when Ulstein had to diversify its operation and work on new vessel segments. Consequently, Ulstein initiated in 2015 an adaptation of its conceptual ship design process. This research work is a fundamental part of this adaptation effort.

Today, Ulstein initiates its design processes by identifying the needs and expectations not only from the shipowner but from the rest of stakeholders involved in the design process. Further, the set of vessel requirements are critically reviewed and agreed upon before work on the actual ship design takes place. This initial phase is supported and structured by the development of a vessel business case, which: (i) supports the generation of relevant information in early design phases, (ii) builds a bridge among stakeholders' expectations and (iii) supports the balancing of the vessel design in terms of commercial, operational and technical aspects.

The focus of this research, as reflected in Figure 1-1, is in the earlier phases of the ship design process, including the development of the business case and the development of the conceptual ship design, with less emphasis on downstream activities like basic design and detail engineering.

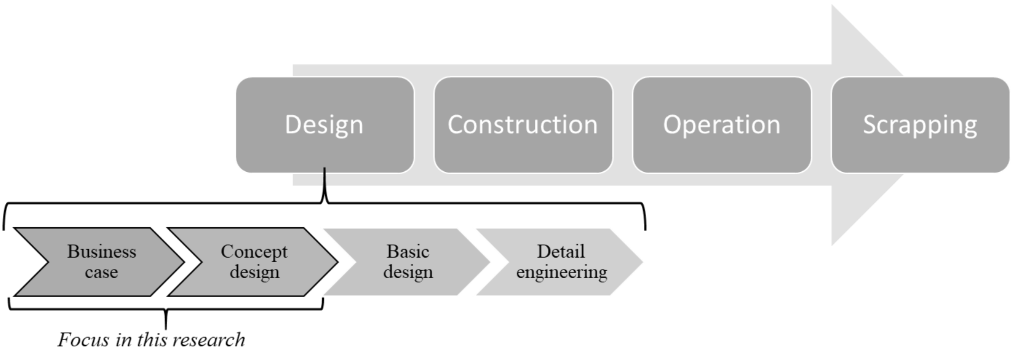

Figure 1-1 Ship design process as a part of the lifecycle of a vessel.

In the following chapter, I will explore the generics of conceptual ship design and find out what are the factors contributing to effective ship design and how they are influenced by uncertainty.

1.1. Background

The ship design process is a critical and complex decision-making process (Gaspar, Erikstad and Ross, 2012; van Bruinessen, Hopman and Smulders, 2013; Jain, Pruyn and Hopman, 2015), which leads from a set of given vessel expectations to a fully operational system definition and description (Ulstein and Brett, 2015). Designing a ship requires a multidisciplinary consideration in arriving at relevant design objectives and setting design constraints (Deb *et al.*, 2015). All of this being influenced by multiple uncertainty factors that can reduce the effectiveness of the ship design process.

Effectiveness in decision-making in the ship design process consists of several issues, as illustrated in Figure 1-2. One of these issues is the selection of a better vessel design solution among peer solutions. The selection of a design alternative shall be taken considering that the vessel will perform a mission or set of missions during its lifecycle. Such a set of missions involve the expectations and constraints imposed by all stakeholders. These expectations and constraints should reflect current and both, current and future market needs and conditions (Ulstein and Brett, 2012; Gaspar, Brett, Erikstad, et al., 2015). One could say that the final goal of the ship designer is to develop "the right vessel for the right missions over time" (Gaspar, Brett, Erikstad, et al., 2015). The process of integrating performance capability, operability and economic effectiveness over a vessel's lifetime during the initial design stage represents a challenge to designers. At this stage, the level of design knowledge is typically low, and uncertainty higher as to the market situation retention and the long-term expectations for the vessel design solution. Undetected errors in the specification of the vessel requirements can have significant effects on cost and time spent in designing complex systems such as ships (Sikora, Tenbergen and Pohl, 2012). Thus, proper requirements' elucidation is important (Andrews, 2011).

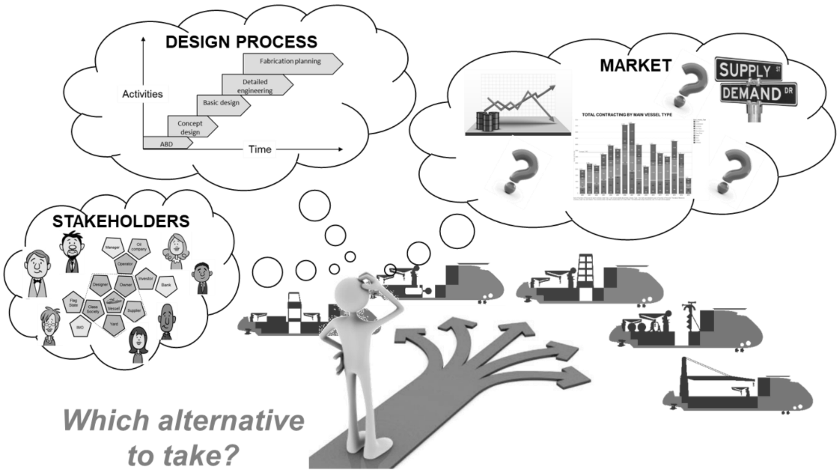

Figure 1-2 Ship design decision-making dilemma.

Vessels are typically designed and built for being in operation for 15 to 40 years. Some are developed for a specific contract, which covers their entire lifecycle, others based on a 5- or 10-year contract and some are built for speculation[1]- to be re-letted to other takers or investors after they have been constructed and delivered. In some cases, the ship is built with the unique intention of being sold at a higher price later on, under the expectation that the value of it has appreciated. Different company strategies lead to different needs and expectations for a vessel design. It is, therefore, paramount to frame the vessel design process in the right context and ground it in specific business case premises (Brett *et al.*, 2018). When those market or customer needs and expectations are ambiguous, or they are not easy to foresee and define, the decision-maker needs alternative methods to handle this uncertainty. In this way, the stakeholders can come up with the better vessel design solution to fit the uncertain market, operational and technological demands. This is what Andrews (2003, 2011) names the *wicked problem*. Experience suggests that when a large number of uncertainties have to be handled at the same time, complexity increases intensely, and the effectiveness of the decision-making process is lowered (Gaspar, Hagen and Erikstad, 2016).

The most common way to handle uncertainty in ship design processes, today, is by adding margins and/or safety factors, in order to ensure a minimum acceptable performance level (Meyer, 2002). Uncontrolled use of margins can easily lead to non-competitive ship design

[1] Construction with no formal commitment from the end users of the finished product. In shipping industry, this is referred to those newbuilding contracts signed before the vessel has been contracted for a specific operation.

solutions; too heavy structures, overpowered vessels or underutilized cargo holds. Lately, the use of frameworks for system design under uncertainty such as the Ulstein Accelerated Business Development approach (ABD), Epoch Era constructs, stochastic optimization techniques and real options have been successfully applied in ship design and operation to evaluate uncertain future operating performance (Brett, Boulougouris, *et al.*, 2006; Sødal, Koekebakker and Aadland, 2008; Rader, Ross and Rhodes, 2010; Gaspar *et al.*, 2012; Andrews and Erikstad, 2015; Keane, Gaspar and Brett, 2015; Pettersen, 2015; Plessas and Papanikolaou, 2015).

1.2. Problem statement

Uncertainty handling is, in many cases, a major limitation to effective decision-making in vessel design (Erikstad and Rehn, 2015; Garcia *et al.*, 2016). Ship design, especially complex vessel design such as offshore, cruise and naval vessels, is a specific client-oriented industry or Engineering to Order (EtO) business where, in most cases, each ship design is modified, adapted and developed for a specific client (van Bruinessen, 2016), to be operated during a relatively long period (15 to 40 years) in a typical, VUCA[2] environment (Keane *et al.*, 2017). In addition to the intrinsic complexity of the vessel design (Gaspar *et al.*, 2012), the context where it will operate and the stakeholders involved in its design, construction and operation challenge the development of an optimized, ideal vessel. The increased interest in how uncertainty challenges the prediction of future needs and operating conditions (Broniatowski, 2017b) and the ambiguity of what are the true needs, are triggering the necessity of new ways of approaching the concept design development phase (Haberfellner and de Weck, 2005). Further, some techniques to guide owners and designers on what is a better ship have been recently proposed (Ebrahimi, Brett, Garcia, *et al.*, 2015; Ulstein and Brett, 2015), hence contributing to the reduction of uncertainty regarding when to stop the exploration phase.

Traditionally, ship design has been carried out following the design spiral (Evans, 1959), an iterative process starting with some initial expectations from the customer (a ship owner, operator, investor or a combination of several parties), and looking for the optimization of a marine platform towards a specific goal, viz.: low fuel consumption, high cargo-carrying capacity, high safety; exemplified in the Design for X strategies (Papanikolaou *et al.*, 2009). Conceptual ship design represents the first turn of the design spiral (see Figure 1-3 – left). This approach presents a challenge when handling unclear expectations, since these expectations may change as more information about the design become available – reducing the uncertainties under which the key expectations are defined and concluded (see Figure 1-3– right). Six main challenges are faced when carrying out this traditional methodology in early concept development under uncertainty (adapted from (Ulstein and Brett, 2012)): (i) long and expensive *trial-and-error* process; (ii) challenging quality control and assurance; (iii) ineffective communication and decision-making; (iv) expensive and very context-sensitive designs; (v) lack of integration among technical, commercial and operational aspects and (vi) weak or inexistent life-cycle assessment.

[2] VUCA relates to Volatility, Uncertainty, Complexity and Ambiguity (Bennett and Lemoine, 2014).

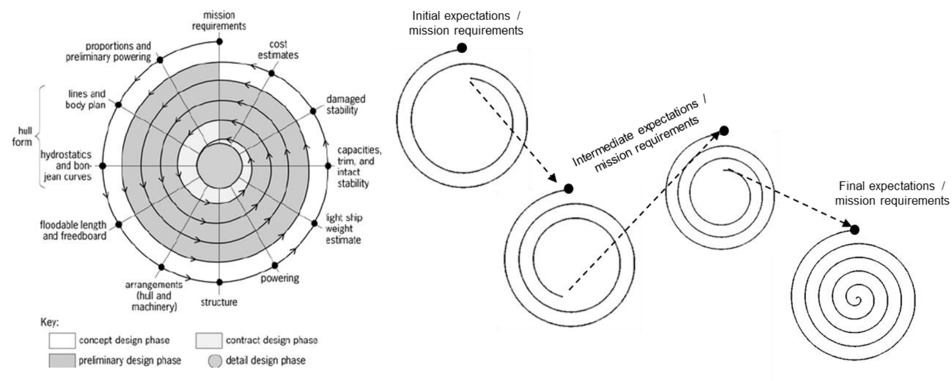

Figure 1-3 Ideal ship design process (left) (Evans, 1959) vs real ship design process (right).

Design is generally described as a purposeful decision-making activity motivated by the satisfaction of some specific needs and expectations (Archer, 1969; Coyne *et al.*, 1990; Suh, 1990). Problem definition, as the first of the four steps in the design process (Figure 1-3), plays a critical role in the generation of effective designs (Suh, 1990). This is, however, not a straightforward activity in ill-structured problems (Walker, 2013), since every mission and stakeholder will typically imply a different set of expectations and constraints. These type of problems, also described as the wicked problem (Andrews, 2012), have no stop-point rule and its solutions are not true or false, but rather better or worse (Ison, 2010). The problem definition of ill-structured problems requires a holistic evaluation combining strategic, tactical and operational decisions, trying to answer questions such as: what is needed? (Ulstein and Brett, 2015) How can it be fulfilled? Will the need remain constant over time? What can affect it and how much? Who is affecting the need and how much? This becomes then an argumentative process through which a solution emerges gradually as part of the critical review of the problem (Ison, 2010). Understanding all these questions will give us a better idea of why optimizing for an ideal likely future is not good enough.

The technical focus of ship designers challenges the solving of wicked problems (Rittel and Webber, 1973). In these multidisciplinary fields, very often each domain expert will develop his/her own understanding of the problem and propose a better solution based on a mono-disciplinary perception (Veeke, Lodewijks and Ottjes, 2006). Ill-defined problems require holistic thinking in contrast to relying only on purely technical considerations (Ison, 2010). A soft systems approach which can deal with different perceptions and facilitate a common agreement on expectations and constraints is required (Veeke, Lodewijks and Ottjes, 2006).

The design decision-making problem, including technical, commercial and operational decisions, is influenced by two main elements, a context or environment where the decisions take place, and the agent(s) or decision-maker(s) participating in it (Fantino and Stolarz-Fantino, 2005). The lack of perfect information regarding the environment (or context) and agent(s) behaviour and expectations are the principal sources of uncertainty in decision-making problems (Kochenderfer, 2015). Context factors represent the characteristics of the environment in which the decision is made (Kahneman, 2000). They are external elements influencing the decision-making process that, in most cases, cannot be directly controlled by the decision-maker (Fantino and Stolarz-Fantino, 2005). The final decision will depend extensively on the contextual information available (Busby and Hibberd, 2002). Human behaviour relates to the attitude of the agents towards decision-making; the way needs are perceived, and performance is measured. Agent's attitude or behaviour is influenced at the same time by the context (Norman, 2005). Agent behaviour represents a broad term in this work. It relates to the influence of the decision-makers and the interactions among them in the decision process. In multi-stakeholder problems, Norman (2005) argues that what is one person's acceptance could be another one's rejection. For example, a ship designer may consider a feature essential while the shipowner doesn't. Human decision exhibits a large suboptimal variability whose origin and structure remains poorly understood (Wyart and Koechlin, 2016). This suboptimality challenges the effectiveness of the decision process. The integration of needs, expectations, and requirements in design projects involving multiple stakeholders, as is the case of ship design (Ulstein and Brett, 2009) or shipping in general (Stopford, 2009), is an important challenge. Traditionally, multi-stakeholder design problems have been solved collaboratively, based on aggregation strategies (Broniatowski, 2017a). However, this aggregation strategies, consisting of the superposition of expectations, often end up with overspecified, gold plated solutions (Garcia *et al.*, 2019). Both uncontrollable context factors and unpredictable human behaviour are the roots of irreducible uncertainty in decision making (de Weck, Eckert and Clarkson, 2007; Gigerenzer and Gaissmaier, 2011), which may be referred to as randomness (Thunnissen, 2003).

Recent market factors have shown how newer vessels in the offshore supply fleet (OSV) seem to have a lower competitive performance compared to older peer tonnage (Garcia, Brandt and Brett, 2016b, 2016a). A brief review of previous designs and their development processes show how a period of relatively high oil prices (2005 – 2014), defined as the *Golden Era*, changed the behaviour of market players with respect to what was really needed – "nice to have" versus "must have". Strong market dayrates and compensation of overperforming vessels led to a *more is better* strategy in offshore vessel design. From an economic perspective, Lucca, Roberts and van Tassel (2017a, 2017b) support the appearance of this practice, arguing that investors increase their tolerance to risk - will be willing to take more risks - after a period of lower volatility, as it was the offshore oil & gas (OO&G) market during the period 2011 to 2014. The standard deviation of the monthly oil prices, an indication of the market's volatility, was in the period 2011/2014 of 6.3, compared to 21.2 in the four-year period preceding (EIA, 2018).

Uncertainty during the conceptual ship design development process can affect negatively the perception of the customer toward the project at hand and, therefore, reduce the efficiency of the decision-making process. Cleanthous *et al*. (2016) demonstrate the generation of worry and anxiety due to uncertainty in medical patients treatment. Such worry and anxiety affect negatively treatment adherence and the general well-being of patients. Based on the findings of Cleanthous et al., we can argue that reducing the level of perceived uncertainty by the customer leads to an improved likelihood of winning the contract for the designer.

Because the shipping industry is full of uncertainties, historically it has been considered as a risky industry (Stopford, 2009; Oltedal, 2011). Hence, its development has been strongly influenced by a regulatory framework (IMO, 2013) which, following a risk management approach, focuses on the treatment and transference of technical and operational risk rather than on its termination. But the effects of uncertainty, contrary to risk, can also include upside opportunities (Hillson, 2002). Thus, reducing uncertainty handling to only risk management limits the ability of the decision-maker to face uncertainty. Although decision-makers would like perfect certainty regarding the outcomes of their actions (Thissen and Agusdinata, 2008), a large number of problems require that decisions have to be made in the presence of uncertainty (Sahinidis, 2004; Bradley, 2012; Kochenderfer, 2015; Kwakkel, Haasnoot and Walker, 2016). In decision situations under uncertainty, it is important that the decision-maker understand both, the potential negative consequences and upside opportunities that may arise when uncertainty appears or is recognised.

1.3. Lessons from experience

Design is about making decisions based on the maximization of the value or utility perceived by the different stakeholders (Stigler, 1950; Hazelrigg, 1998; Mongin, 1998). In most of the cases, decision-makers in the shipping industry act capitalistically pursuing a short-term economic benefit (Borch and Solesvik, 2016). Design projects in the ship design industry start from the specification provided by a customer and building on it (Hazelrigg, 1998). The value, utility, or performance indicator used to compare alternatives and driving the design process is, in many cases, ill-defined (Pettersen *et al.*, 2018). It is our experience that the conceptual design phase in many projects is unnecessarily extended upon, both in time and use of resources, as a consequence of the poor and unclear definition of initial expectations. Ship designers very often start developing a vessel design solution based on the wrong set of expectations, requirements and constraints.

This intrinsic uncertainty characterising the development of requirement in new vessel design projects leads, often, to make decisions based on heuristics, nose, or stomach feeling (Parker, 2016). The same practice has been identified in risky situations (Riabacke, 2006). Expectations, requirements and constraints are settled without understanding the consequences they may have in the final vessel design solution. One of the principal reasons behind this behaviour is that ship design firms and their naval architects are more comfortable operating as *technical* consultants rather than ship designers. A ship designer must use the expectations of the customers to guide them into what is a better vessel for their company, considering also operational and commercial matters. Today many ship design firms limit their scope to calculate weights, stability and draw general arrangements, without looking into what the vessel is intended for. Thus, we as naval architects are easily uncomfortable working with ill-structured or wicked problems and see difficulties to look outside our design-guidelines for alternative answers to questions that customers initially are incapable of answering. Uncertainty in the expectations of a new vessel design, which gives freedom to the ship designer as to what to work with, maybe perceived negatively by today's naval architects. Hammer and Champy (1995) suggest that the uncertainties hammering the business proposition are, typically, those outside the initial expectations. Thus, the ship designer has an important role as a provider of recommendations to the shipowner.

Communication among ship design firms, their naval architects and marine engineers, and their customers is an influential factor to the effectiveness of the design process. Uncertainty regarding contractual aspects is always influencing communication among stakeholders. What does the customer mean by a preliminary general arrangement? Should it represent 10 hours or 50 hours of work? What is meant by “modern look”? We at Ulstein have frequently experienced some of these uncertainties in the more than 100 vessels designed and built at own and international shipyards around the world. Language is one of those aspects contributing to miscommunication in projects. Although most of the companies involved in the maritime industry are relatively fluent in English, not everyone is able to communicate effectively, either written or verbally, to the same level as in their original language. In some cases, all the official documentation and information is available in the customer’s original language only, so intermediary companies without maritime background, or online translator websites, have to be used to translate the documentation. Some suppliers provide information about their products only in their original language too. Uncertainty is basically appearing in almost aspects of and phases of the ship design process. Hence, I find the uncertainty aspect appearing in the conceptual ship design process intriguing, and its apparent effect on the effectiveness of the design process challenging.

1.4. Research goal

Thus, the goal of this PhD research is to enhance the knowledge of how uncertainty arises in ship design processes and, how it influences the conceptual ship design and the complementary decision-making process. By identifying, categorizing and ranking the principal sources of uncertainty affecting the ship design decision-making process, this research work aims at: (i) recognise the factors influencing the overall uncertainty level, (ii) identify those with the highest influence, and therefore (iii) suggest measures to be taken in order to improve the efficiency of the process by better handling its inherent uncertainty.

This research focuses on the handling of uncertainties in the conceptual ship design phase. The overall objective of this PhD research identifies uncertainty sources (construct characteristics) affecting the conceptual design phase of new vessel designs to improve the way of how uncertainty can be handled in the design process and consequently enhance the overall effectiveness in decision-making.

1.5. Research questions

The importance of uncertainty in ship design decision-making deserves to be further explored to improve the effectiveness of the conceptual design decision-making process. Understanding what uncertainties are affecting the selection of functional requirements and performance expectations during the conceptual ship design process is a pre-requisite to select an appropriate uncertainty handling strategy – whether (i) ignore it, (ii) delay the decision,(iii) reduce it or (iv) accept it (Thissen and Agusdinata, 2008). These strategies may be seen as adaptations to the 4T's of risk and loss control management literature: terminate, treat, transfer or tolerate (Bird and Germain, 1985). Therefore, it is necessary to further research regarding what uncertainties are really perceived by the different actors during the design process and what uncertainties are influencing the outcome of a ship design decision-making process. Finally, it should be evaluated what existing methodology could be applied in ship design processes to reduce the level of uncertainty under which decisions are taken. This can be captured in the research questions as defined below:

What are the important uncertainties in conceptual ship design, and how do they influence effective decision-making?

These research questions will be explored using a mixed-method denominated *exploratory design research* (Leedy and Ormrod, 2015). It consists of exploring a phenomenon based on a qualitative evaluation and then probing quantitatively the extracted hypothesis (Subedi, 2016). The initial analysis requires a deep evaluation of uncertainties as perceived by the different actors involved in the conceptual design phase of new ships. An extensive literature review study is carried out to explore the role of uncertainty in ship design decision-making. An investigative model is developed based on this literature study. Further, our investigative model is tested using multivariate regression analysis. The data analysed was collected through an electronic survey. A survey was considered to be the most relevant data gathering technique for this study. It will allow international spread, as well as the anonymity of the respondents, which typically makes the respondents be more truthful than, for example, in an interview (Leedy and Ormrod, 2015). An overall analysis of the fleet will give valuable information regarding differences among vessel types, at the same time that expanding the potential targeted audience for the survey. A narrower but deeper analysis targeting only one vessel type would reduce the number of respondents required, but it could generate biases towards that specific vessel segment. Hence, a narrower analysis will limit the applicability of the findings.

2. Literature review

This research applies a special version of the between-method type-triangulation of the research problem, where literature from different disciplines and/or research fields is revised in the search for a better explanation of the research problem (Denzin, 2009). The overlap of disciplines relating to the research problem offers an opportunity to redefine existing issues in the field by providing the opportunity to “revise accepted assumptions” and “generate better ideas through academic entrepreneurship” (Zahra and Newey, 2009, pp. 1070–1071). This study is initiated by exploring four complementary research perspectives converging in this research work: (i) decision-making, (ii) (ship) design, (iii) strategic management and (iv) uncertainty in decision-making. The reason for choosing more than one perspective is that ship designers do more than only design, they are decision-makers and strategists in addition (Brett *et al.*, 2018). Further, and following the recommendation of Creswell (2014) and Powel, Lovallo and Fox (2011), a combination of multiple perspectives can neutralize the weaknesses and biases that the individual perspective could bring into this research.

It is the ship design process that constitutes the problem at hand in this research work. The four research perspectives selected and used to explore the research problem are exposed in Figure 2-1. Understanding how the context within which the ship design takes place, and how the ship design decision-making process takes place, are essential to understand how uncertainty is generated and its consequences in the design process. The literature on ship design provides a foundation with the characteristics of the problem and decision-making explains how decisions are taken and what is influencing them. Strategic management literature contributes to this research problem by defining the basis for dealing intelligently with uncertainty in decision-making processes (Levinthal and March, 1993). Finally, the uncertainty literature supports the identification of uncertainty factors and the characteristics associated with them.

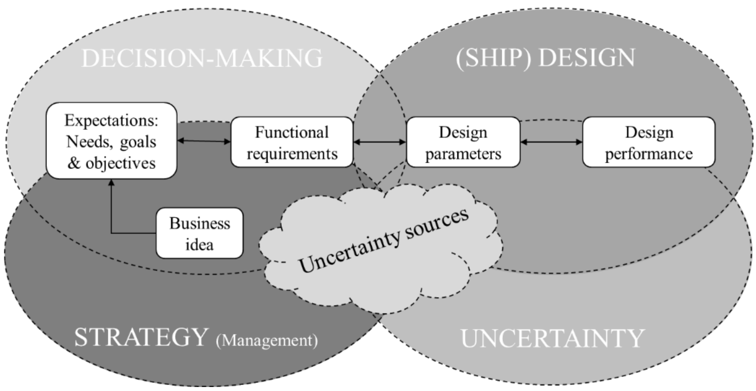

Figure 2-1 Research perspectives in this research work.

Two complementary approaches, a *bottom-up* and a *top-down* strategy, were initially identified and pursued in the process of identifying and analysing of relevant literature. A bottom-up approach starting with specific uncertainties and current practices for handling uncertainty in the shipping industry (like for example the work on *Uncertainty in Bollard Pull Predictions* by

Vrijdag, de Jong and van Nuland (2013)), and looking for causes and reasons of those uncertainties. On the other hand, the top-down approach pursues a deeper understanding of the ship design and the decision-making process to narrow down the factors influencing uncertainty generation. Supported by the four research perspectives mentioned above, it has been possible to generate a mind map presented in Figure 2-2. This mind map represents the interconnections of research disciplines with their specific research concepts and has been built up upon the ideas collected from the articles and books reviewed in each of the disciplines. This mind map has been used as a systemic way of organizing our literature review and research in general (Easterby-Smith, Thorpe and Jackson, 2008).

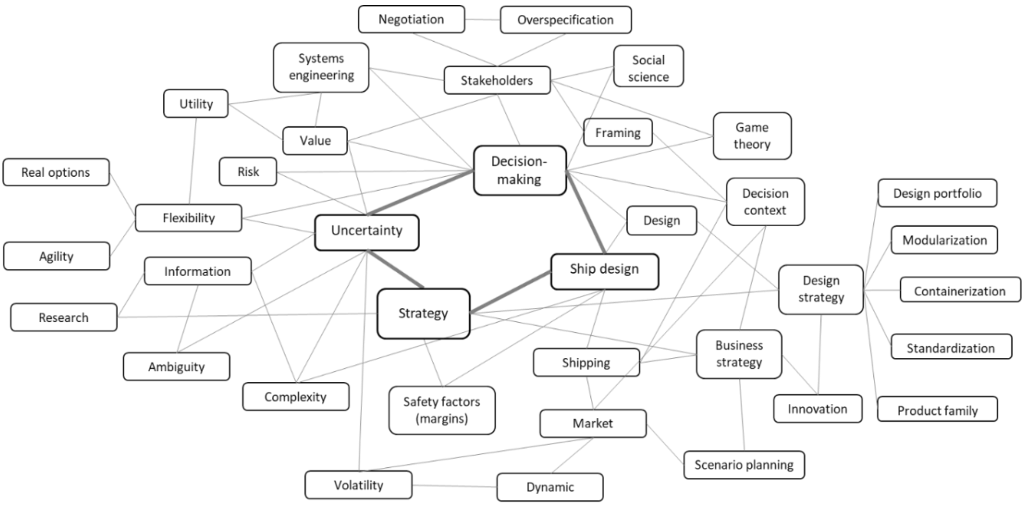

Figure 2-2 Mind map of the literature review research work.

Most of the literature reviewed in this research work expands over a period of more than 50 years, ranging from 1960 to 2019. Only 14 out of more than 650 references consulted were published before this period. These are historical references such as Knight's (1921) *Risk, Uncertainty and Profit* or Nash's (1953) *Two-Person Cooperative Games*. The histogram of consulted references presented in Figure 2-3 reflects a growing trend with a peak in 2015, 2016 and 2017, accounting for 53, 62 and 45 references respectively. The distribution reflects that 25% of references were published before 2000, and the remaining 75% after this year. There are, however, some variations regarding time distribution among the topics reviewed. For example, almost half of the publications from decision-making literature were published before 2000, while more than 50% of the publications on uncertainty are from after 2010. Publications from the period 2015-2019 account for 30% of the total, which reflects the parallel development with alternative, ongoing research.

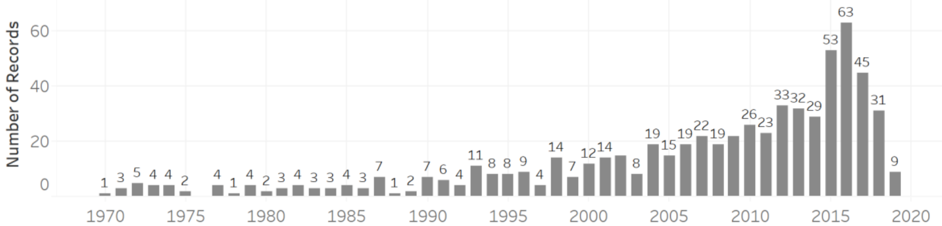

Figure 2-3 Historical distribution of publications reviewed (1970 – 2019).

The majority of the publications reviewed (53%) consist of journal articles. Three journals in particular *Research in Engineering Design*, *Administrative Science Quarterly* and *Ocean Engineering* were of special relevance, with 14, 10 and 10 articles respectively. The second largest group were conference articles, accounting for 19% of the total. The *International Marine Design Conference* (IMDC) was of strong relevance for the topics reviewed, with a total of 18 publications consulted.

Books were also an important reference source for this work, accounting for 12% of the total sources reviewed. Most of the material consulted in books did relate to the topics: decision-making, research methodology and management theory. Articles from scientific publications such as *Harvard Business Review* and *MIT Sloan Management Review* were reviewed to reflect ongoing research by industrial parties and universities, which may not be available in scientific journals or conferences. Finally, the literature review work was complemented with relevant MSc and PhD theses, working papers and reports, although to a lesser extent.

There exists an extensive literature on the topics of decision-making, (ship) design, strategic management, and uncertainty. However, fewer authors have explored their interrelationships. Some authors stand out as key contributors and have a special influence on this thesis. In Table 2-1 the most influencing authors are listed and categorized according to the research perspective. It is recognised that these authors share commonalities with the present research work, in some cases on a more general perspective (e.g. the study of decision-making) and others more closely related to the topic of ship design under uncertainty.

Table 2-1 Most influencing authors by research perspective.

Decision-Making	**(Ship) Design**	**Uncertainty**	**Strategy**
Gigerenzer, G.	Andrews, D.	Cameron, B.G.	Lawrence, P.R.
Hazelrigg, G.A.	Brett, P.O.	de Neufville, R.	Lorsch, J.W.
Kahneman, D.	Erikstad, S.O.	de Weck, O.	Porter, M.E.
Keeney, R.L.	Gaspar, H.M.	Downey, H.K.	Raiffa, H.
March, J.G.	Singer, D.J.	Miller K.D.	
Simon, H. A.		Walker, W.E.	
Tversky, A.			

The literature review was carried out by combining in-depth topic evaluations and exploratory reading. Figure 2-4 indicates the number of new references reviewed per month during the research period. The bulk work on literature review, as predicted from Figure 2-4, took place in the second quarter of 2017. The categorization of uncertainty and the development of the investigative model were carried out during this period. After this period, and as expected, the number of new references explored per month has declined. There are two main reasons explaining the distribution of the histogram shown in Figure 2-4. The first reason is the fact that the initial phase corresponds with the exploration phase, where the research problem is explored in broad. The focus of this initial phase was to read, interpret and summarize the findings from the literature reviewed. The second reason is that the final phase of the research process consisted of data analysis and writing of the thesis. This phase didn't require the exploration of new literature, although it required revisiting previous literature already identified in the initial phase of the research process. On average, fifteen new references were explored per month during the PhD research work period (01.2016 to 09.2019).

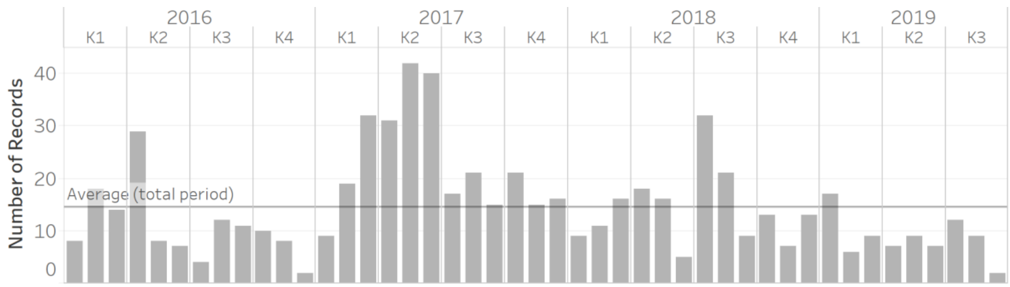

Figure 2-4 Historical distribution of references review throughout this research work.

2.1. Decision-making

The term decision-making was introduced to the business world sometime during the last century by Chester I. Barnard (1886 – 1961). Decision-making replaced terms as *resource allocation* and *policy-making*, changing the way how managers thought and executed their decisions. While policy-making could go on forever, the decision aspect implies the end of a process and the beginning of an action (Buchanan and O'Connell, 2006). Today, decision-making is defined as the "action or process of taking [important] decisions", "a conclusion or resolution reached after consideration" (Oxford University Press, 2016). Building on these definitions, it can be said that every decision involves at least three elements, what we want, what we know and what we can do (Skinner, 2009). The decision-making process guides the decision-maker to identify preferences, expectations, and values (what we want), and choose among a set of alternatives (what we can do) based on the information available (what we know). Collectively these three elements represent the decision basis, and if any of them is missing, there is not a decision to be taken (Howard and Abbas, 2000). A combination of those three elements is the logic of the decision-maker, who evaluates which of the alternatives better fits the needs based on the information available. These three plus one elements (expectations, alternatives, information and logic) of a decision have to be put into a specific context or frame which characterizes the decision situation. Howard and Abbas (2000) exemplify this with a three-legged stool. In the following paragraphs of this subchapter, we will explore each of these elements separately, identifying their role in decision-making and its relationship with the other elements.

One of the critical aspects of decision-making is the fact that decisions are irrevocable (Skinner, 2009, p. 11). Once a decision is taken, it is normally not possible to completely reproduce that decision situation. As Hofseter puts it "A basic fact of life is that time goes only one way" (Hofstede, 2001, p. 145). Hence, although a decision may be reversible in term of consequences, it is not possible to go back in time and replicate the exact decisive moment. In most cases, decisions are taken in the present, based on information from the past and to become effective in the future. This brings us to the second aspect of decision-making, the fact that most decisions are characterized by incomplete certainty regarding their outcomes. Either, there is a situation with little or no historical data, or the decision-maker has not sufficient time to process all the information available (Robinson *et al.*, 2017). The third aspect of decision-making is that there is some leeway about the time of making a decision, so one may decide to postpone it to gain additional information (Dixit and Pindyck, 1994).

As a consequence of these characteristics, uncertainty is an inherent part of decision problems (Atkinson, Crawford and Ward, 2006; Saunders Pacheco do Vale and Monteiro de Carvalho, 2014). Iyengar (2010) argues that it is uncertainty that gives the value to the decision-making activity – and associated responsibility to the decision-maker. And McNamee and Celona (2008) strengthen this idea suggesting that true decision-making takes place only when uncertainty is involved. It is for this reason and for the potential negative consequences that making decisions under uncertainty can entail, that the research community has paid special attention to the topic. Today, the research within decision-making under uncertainty involves, among other disciplines: natural science (Simon, 1996), social science (institutionalism (Stacey, 2010)), systems theory (Ross, Rhodes and Hastings, 2008), political science (Walker, Marchau and Kwakkel, 2013), mathematics (von Neumann and Morgenstern, 1944), economics (Trigeorgis, 1995), psychology (Holmes, 2015), law (Macharis, Turcksin and Lebeau, 2012) and design (Wynn, Grebici and Clarkson, 2011), and not less importantly, ship design (Erikstad and Rehn, 2015). The multidisciplinary of this research topic is reflected in the design models and theories reviewed later in this chapter. In general, all these theories for decision-making under uncertainty share three principles: objects of choice (alternatives), a valuation rule (utility or value function) and mapping functions relating uncertain events to the possible outcomes (Tversky and Kahneman, 1992).

2.1.1. Decision-making process

We may describe the decision-making process as a sequence of stages linked by feedback loops (Alexander, 1982). This process of arriving at a choice is categorized by Simon (1960) in three stages viz.: *intelligence*, *design*, and *choice*. The intelligence phase consists on the identification of the need for taking a decision (what we want), which indirectly involves a previous selection of a set of stakeholders or decision-makers (Fülöp, 2005) and subsequently the context where the decision will take place (Howard and Abbas, 2000). In some cases, rather than pursuing a need, the decision pursues an opportunity, e.g. doing the same as a competitor (Nutt, 2007). Following, the design phase consists of the definition of the alternatives of choice and the description of the problem domain (Dillon, 1998). Alexander (1982) describes the design stage as a combination of search and creativity; consisting of a rational element containing a systematic (or heuristic) search for information, and a creative process of combining it into novel associations. Finally, choice represents the act of deciding one of the potential alternatives. Each of the three phases is a decision in itself (Simon, 1960). The design stage, for example, requires assumptions and presumptions on the generation of alternatives that are choices in itself. These three stages of decision-making are common in problem-solving activities (Stair and Reynolds, 2010). A full problem-solving process includes, additionally, *implementation* and *monitoring* activities. These two activities follow choice, as presented in Figure 2-5. The implementation of the choices is considered as a part of the decision process itself by Skinner (2009), who suggest that implementation also requires decision-making.

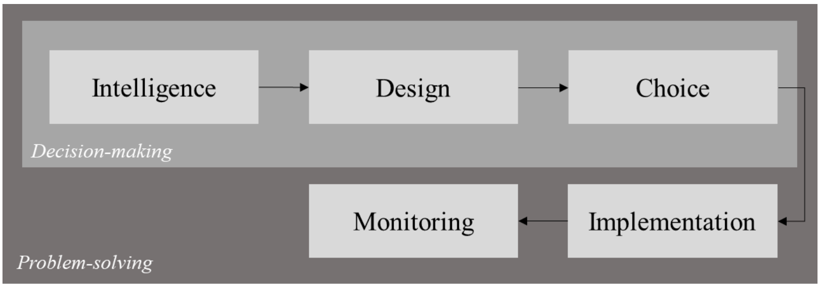

Figure 2-5 Problem-solving process model. Adapted from (Stair and Reynolds, 2010, p. 395).

In a broader perspective, every decision-making process could be seen as constituted by two phases, a divergent phase of exploration and knowledge gathering, and a convergent phase of focus and conclusions (Turpin and Marais, 2004). Additionally, framing is required to define the context and the stakeholders involved in the process. A more detailed description of the decision-making process is proposed by Fülöp (2005), who defines eight steps in every decision: (1) define the problem, (2) determine requirements, (3) establish goals, (4) identify alternatives, (5) define criteria, (6) select a decision-making tool, (7) evaluate alternatives against criteria, and (8) validate solutions against problem statement. The selection of a decision context and the decision-makers are considered early steps in his model. A proposal of how these eight steps could be integrated into the three stages proposed by Simon (1960) is suggested in Figure 2-6. The first three steps relate to the intelligence phase, where the problem is identified, and a set of preferences and goals are drawn up. Then comes the design phase, relating to the identification and description of the alternatives of choice. Finally, the choice phase consists of four steps. This step consists primarily on the definition of a set of criteria to evaluate alternatives and the selection of an alternative based on such criteria. Two further steps are considered in (Skinner, 2009): (9) allocate appropriate resources and (10) implement a course of action. A more detailed literature review of decision-making processes is presented by Negulescu (2014).

Looking in detail at a traditional vessel newbuilding project from the perspective of a shipowner, we can relate the different activities to the steps and phases of the decision-making process model in Figure 2-6. The project initiates with a need (or a problem), a new tender, a vessel that has to be replaced or a desire to expand the fleet. The need or problem is defined by a set of expectations, whether taken from the tender document or defined by the shipowner itself or other stakeholders, very often the charterer and end-user of the vessel. The project shall be complemented by a set of goals, such as winning the tender, obtain a specific return on equity (or profit), improve the general perception of the company, etc. This information is then transferred to one or several ship designers, who will provide a set of design alternatives for the shipowner to choose among. Presented with a set of alternatives the shipowner has to decide criteria to choose among them and evaluate the different alternatives according to those criteria. In some cases, computer tools, benchmarking tables, or other techniques can be used for this purpose. The final step is to check if the selected alternative fulfils the set of goals and expectations defined in step 2 and 3, and whether it solves the problem or accomplishes the need it was intended to cover.

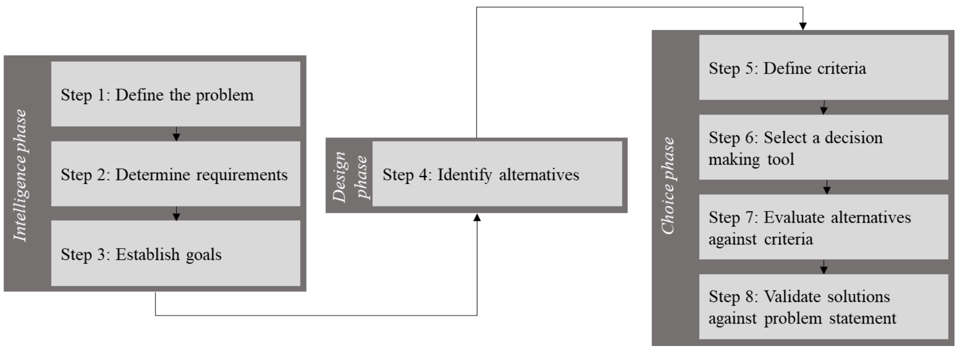

Figure 2-6 A model of a typical decision-making process in ship design.

Although the decision-making processes are modelled in Figure 2-5 and 2-6 as linear processes, reality is more complex. As Skinner puts it, “Decision analysis is as much, if not more, a way of thinking and dialoguing than a formal process with many steps” (Skinner, 2009, p. 103). Decisions influence positively and negatively one another (Gonzalez, 2005). For example, the choices made in step 2 and step 3 will affect the type and number of alternatives identified in step 4. Hence, if the decision-maker does not identify an alternative he or she was expecting to find, he or she has to go back to step 2 and redefine its choice, so when back in step 4, the expected alternative is available. Robinson *et al*. (2017) try to demonstrate in their research the fluidity, multilayered and non-linearity of decision situations by analyzing daily decision tasks of thirteen academics and practitioners in decision science. Their findings suggest that decision-makers, consciously or unconsciously, rely on the nonlinearity of decision-making processes (feedback and feedforward) to reduce the comfort that uncertainty and ambiguity produce to them. Thus, the decision-making process has to be flexible and scalable, adapt to the variety of natures of the decision problem and has to allow for forwarding and backward loops among the different steps.

One aspect breaking the linearity of decision-making processes is the fact that the decision context changes along with decision-makers actions and vice-versa (Edwards, 1962). This is a characteristic of dynamic decision making (DDM), where decisions depend on former decisions, and where its consequences depend on the environment, which may vary spontaneously and as a consequence of earlier decisions (Fischer, Greiff and Funke, 2012). In those DDM situations, decision-makers can rely on decision support techniques including: (a) outcome feedback, (b) cognitive feedback or (c) feedforward; or a combination of those (Gonzalez, 2005). These techniques enhance the learning process while taking decisions favouring the reduction of uncertainty and contribute to the overall effectiveness of the decision process (Gonzalez, 2005). For example, using information from experience as a feedforward technique to predict the consequences of choices and causality (Pearl and Mackenzie, 2018).

2.1.2. Decision-making agent

Decision-makers play a central role in the decision-making process. But humans are not *perfect* (referring to "having all the required or desirable elements, qualities, or characteristics; as good as it is possible to be" (Oxford University Press, 2016)). The capacity for taking decisions of a human being is limited by their information processing system, their behaviour in the decision process and their organizational behaviour relating to others (Larichev, 1999). Such limitation factors influence the way human decision-makers identify, perceive and choose among alternatives.

Human decision-makers rely on two systems when making decisions, intuition and rationality. Kahneman (2011) names them *System 1* and *System 2* respectively. System 1 acts fast and operates automatically. Hence, it requires little or no effort. This is an unconscious way of thinking. System 2, on the other hand, focuses on the more complex matters with effortful conscious choices. This system is a controlled but slower way of thinking. Hence, decisions made based on intuition (system 1) rely on the association of ideas. This association is gained through experience. Experience has grown through decisions from system 2. Hence, rationality has the ability of programming the way system 1 thinks (Kahneman, 2011). Human decision-makers will make a choice between these two systems depending on the context of the decision, his or her experience, and the type of decision. Although intuition requires less or no effort, is subject to biases and systematic errors.

The human information processing system is characterized by having a limited span of the working memory. This limitation forces the decision-maker to rely on System 1, even in situations where System 2 should be used. This consist of simplifying the decision situation by means of limiting criteria - heuristics (Tversky and Kahneman, 1974). In addition, as demonstrated by Tversky and Kahneman (1974), humans tend to neglect small differences in the evaluation, which could lead to eliminating dominating alternatives in benefit of dominated ones. Last but not less important, we should expect that humans can err when processing information (Alexander Pope, 1711). The limited capability of humans to understand complex problems and decisions leads us to the use of heuristics as a basis for simplifying the problems and make them tractable (Powell, Lovallo and Fox, 2011). Human behaviour in the decision-making process is characterized by a lack of preconceived decision rules. Typically, a time-consuming process of "trial and error" is carried out in order to gather additional information. Due to the limited capacity for processing information, humans trend to discard alternatives, focusing just on the potentially best ones. This is typically done following specific and personal strategies – biases (Tversky and Kahneman, 1974). As demonstrated by Payne *et al*. (1992), while experienced decision-makers have preferable strategies, novel decision-makers choose the decision strategy based on a compromise between effort and accuracy.

The use of imprecise words, like "likely" or "possibly", also have an effect on the uncertainty perceived in decision-making situations. Both its subjectivity as well as the possibility of different interpretations (Mauboussin and Mauboussin, 2018), may lead to the generation of uncertainty in the interpretation of, for example, user needs and expectations. Nutt (2007) finds that impressionistic approaches of this type lead to poorer decisions. Mauboussin and Mauboussin (2018) recommend the use of numerical probabilities in such circumstances to avoid poor communication and reduce uncertainty in interpretations. Imprecise communication is common in Asian countries, ruled by a listener orientation culture (Gladwell, 2009). Listener orientation relies on the listener to make sense of what is being said, as opposed to transmitter orientation, where is the responsibility of the speaker to transmit a clear and unambiguous message (Gladwell, 2009).

In the cruise industry, is common to define the style of the vessel as luxury, classic, modern, etc. These connotations are difficult to relate to during the conceptual design phase and complicate the work of the ship designer. As a way to reduce the uncertainty generated by this terminology, we at Ulstein have developed a luxury scale to be used in the communication with the customers (Garcia, Brett and Ytrebø, 2018). The luxury standard of a cruise vessel is defined in one scale of five levels, ranging from *modest-luxury* to *ultra-luxury*. Each of these luxury levels has associated a building cost, size of cabins and space for public spaces and becomes reflected on the daily price for the tickets the cruise passengers will have to pay. Thus, the uncertainty of a vague description becomes operationalized through elements that can be understood by both, the ship operator and the ship designer.

2.1.3. Multi-stakeholder decision-making

Engineering systems, such as ships, real estate, and infrastructure projects, have become larger and more complex and may involve large quantities of resources and multi-field expertise (Kusiak and Wang, 1994). Market globalization spurs companies to operate in unknown environments, geographically, culturally, and technically. In addition, global sustainability goals increase the pressure for involving society and the environment in the development of new systems (Bocken, Rana and Short, 2015). Competitiveness is also incentivizing co-creation (Rexfelt *et al.*, 2011) and open innovation in new product development. These and other factors have stimulated the integration of additional stakeholders in systems design (Grogan and de Weck, 2016).

As the number of stakeholders involved in the design process increases, the need for decision support tools and systems that integrate them into the decision-making process increases as well (Topcu and Mesmer, 2017). This is of special importance in the conceptual design phases (Eisenbart, Gericke and Blessing, 2017). In ship design, for example, the decision team will typically include the ship designer and shipbuilder, vessel operator or charterer, end customer and shipowner or investor, among others. A stakeholder-map for a typical cruise vessel project is outlined in Figure 2-7. This shows a broad diversity of disciplines and perspectives within the decision team (Reich, 2010), technical, operational or commercial perspective, respectively. From the mid. 90s, the literature includes a variety of multi-stakeholder cases in fields such as urbanization and logistics (Macharis, Turcksin and Lebeau, 2012; Pooyandeh and Marceau, 2014), product design (Kusiak and Wang, 1994; Alvarado, Rabelo and Eaglin, 2008) and policy development (Ferretti, 2016).

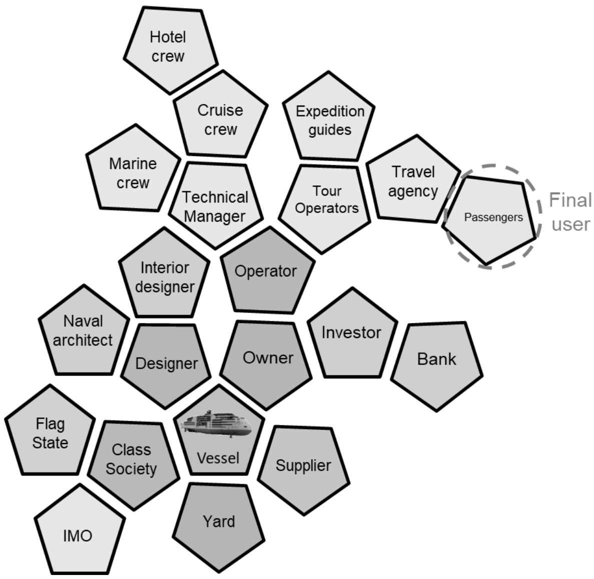

Figure 2-7 Overview of stakeholders typically involved in a cruise ship design.

The difficulties surrounding multi-stakeholder design problems have been widely studied in the engineering design context and has been subject to much debate. Reich (2010) summarizes the conflict by outlining two alternative worldviews, *praxis* and *scientism*: The praxis perspective judges decision-making methods according to the actual improvement of design practices and is supported by the proponents of methods like quality function deployment, analytical hierarchy process (Saaty, 1990), and Pugh controlled convergence (Pugh, 1990; Frey *et al.*, 2009). The scientism perspective, on the other hand, suggests that design decisions should be derived by application of methods that builds on rigorous theory from other decision-making domains, exemplified by the multi-attribute utility (Keeney and Raiffa, 1993) or social choice theory (Arrow, 1950).

Coordination of design activities is paramount to ensure sound decision-making. This process necessitates a continuous exchange of information among the participants (Eisenbart, Gericke and Blessing, 2017), which makes the availability of information one of the most challenging factors in the negotiation process (Pooyandeh and Marceau, 2014). Misconceptions are another characteristic of multi-stakeholder decision problems that may induce failure and errors. Busby and Hibberd (2002) explore misconceptions between designers and operators in the marine and offshore industry, categorizing these in two groups: (i) designer's misconceptions about operators and the operating environment, whether wrong expectations or missed expectations and (ii) operator's misconceptions about the design and designer's intentions. Such misconceptions are more frequent than what one could initially expect, and new technologies are a stimulus of it (Busby and Hibberd, 2002). A good example of this is hybrid propulsion plans in vessels. Hybrid propulsion plants are characterized by a combination of diesel-mechanic and diesel-electric propulsion. The vessel can operate in both models independently of the operation and power required, but to obtain the energy efficiency benefits of such propulsion plant, the operator needs to understand how the plant was originally designed to be operated more effectively. On the other hand, the designer needs to understand how the vessel will be operated, and what type of missions will be carried out during its operational life. The misconception of how the vessel will be operated or how it was designed may result in ineffective operations and unnecessarily high fuel oil consumption.

2.1.4. Decision-making context

Decision-making context (Fantino and Stolarz-Fantino, 2005), environment (Girod *et al.*, 2003; McNamee and Celona, 2008) and frame (Howard and Abbas, 2000; Skinner, 2009), describes the situation in which the decision is taking place, the type of decision and the external factors that may influence the decision. The context in which decisions take place has a major effect on the result of the decision-making process, as it influences all the elements of the decision basis (Howard and Abbas, 2000). In ship design, for example, the status of the shipbuilding industry (dayrates, fuel prices, shipbuilding prices), has shown to have a major influence on the final decisions (Garcia, Brandt and Brett, 2016b). In many cases, the context can explain most of the lack of optimality of many human decisions (Fantino and Stolarz-Fantino, 2005). Time constraint, as a contextual factor, is a critical aspect of decision-making (Robinson *et al.*, 2017). In a time-constrained situation, the decision-maker may put less importance on reliability and precision. Turpin and Marais (2004, p. 154) find that in some situations "60% solution today is infinitely better than a 100% solution tomorrow"; which implies the importance of information in earlier stages of the decision-making process.

Haralick (1983) argues that it is the context which represents the major differences between human and computer decision-making. One example is the work of Pawlina and Kort (2003), who demonstrate the effect of competitors' decisions in the performance and, therefore, the decisions of a company when operating under demand uncertainty. In their analysis, the authors evaluate the asset replacement in a duopoly, where only two firms compete in a market with demand uncertainty. Their findings showed that product demands uncertainty delay decisions and that the investment of one competitor delays even further the optimal investment time for a company. The concept of VUCA environments (Volatility, Uncertainty, Complexity, and Ambiguity) has gained interest among researchers to reflect the challenges that the decision context brings to the decision-making problem (Bennett and Lemoine, 2014). More recently, Robinson *et al*. (2017) suggest that VUCA is not only a contextual factor but also the reflection of the human condition.

Jackson (2003) differentiates among six potential contexts for decision situations depending on two variables: complexity and interaction among stakeholders. Complexity differs between simple and complex contexts, where the former is characterized by few subsystems with few highly structured relations. With regards to the number of interactions among participants in the decision, Jackson (2003) differentiates among three types of contexts; unitary, pluralist and coercive. Unitary contexts are characterized by contexts where stakeholders have aligned values, beliefs, and interests. Contrary, coercive contexts are those where values, interest, and beliefs are misaligned. In the intermediate, Jackson identifies plural contexts as those where stakeholders have compatible interest but misaligned values and beliefs. Another perspective broadly used to categorize decision contexts is the one relating to the amount of clarity of information, or dynamism, identifying three types of contexts: uncertainty (also defined as fuzzy or dynamic), risk and certainty (Luce and Raiffa, 1957).

Some researchers go beyond the term context and relate to *situation awareness*, which brings in the time dimension directly. There have been several definitions of situational awareness proposed over the years, describing it, in general, as "knowing what is going on" (Lo and Meijer, 2014, p. 121). More specifically, situational awareness consists of: (i) the perception of the elements in the environment, (ii) the comprehension of their meaning, (iii) and the projection of their status in the future (Endsley, 1995). Hence, situational awareness brings together the context, in which decisions are made, the process followed to make a decision, and the ability of the decision-maker(s) to interpret and make a decision. Literature suggests that the situation awareness of each decision-maker (or designer in the design process) is crucial in the performance of the decision-making process (Endsley, 1995). However, maintaining and creating situational awareness in dynamic systems becomes increasingly difficult. In ill-structured problems relating to dynamic environments, a major element of decision-makers' role is to build and maintain his or her situational awareness (Endsley, 1995). Endsley (1995, p. 60) suggests that "individuals with good situational awareness will have a greater likelihood of making appropriate decisions and performing well in dynamic systems". In other words, it is as important to define and understand the problem as it is to resolve it.

2.1.5. Research in decision-making

"Classical theories of choice in organizations emphasize decision-making as the making of rational choices on the basis of expectations about consequences of an action for prior objectives, and organizational forms as instruments for making choices" (Dillon, 1998, p. 99). It is likely that most organizations would like to think that they and their employees follow such rational processes; in practice, it is unlikely to happen. Decision-making, as a branch of research, has two main features distinguishing it from other research disciplines (Larichev, 1999): (a) the initial statement of the decision-making process has elements of uncertainty related to lack of information regarding the quality of the solution and the consequences of the decisions, and (b) the decision-making problem typically requires the construction of subjective models, representing the perception of the problem by the decision-maker. These distinguishing features make the role of the decision-maker as a central figure of the decision-making process. The decision-maker role is taken by people (stakeholders), either directly as decision-maker(s) or by defining the rules for machine-based decision-making.

The way managers, designers and in general, every person make decisions, from rare to ordinary decisions, varies considerably. Literature has explored this field both regarding the way in which we should theoretically make decisions and the way we are observed to make decisions. Research on decision-making is often divided into two groups (Elbanna, 2006):

content research, concerned with the basis on which decisions are made, and process research, which deals with the way decisions are made (Regan, 2012). Three perspective theories are here identified in order to classify the way decisions are made (Dillon, 1998). Descriptive, prescriptive and normative decision-making theories follow distinct methodologies for selecting the course of action, to make a choice (Oliveira, 2007), see Figure 2-8. This distinction comes from the two separate roots that decision-making research has followed: economical utility theory and operations research. Descriptive models use cognition to explain decision-making, whereas normative theories are based on rationalistic components that indicate how decisions should be taken. Prescriptive models are based on both, the theoretical foundation of normative theory and the observations of the descriptive theory (Dillon, 1998; Oliveira, 2007).

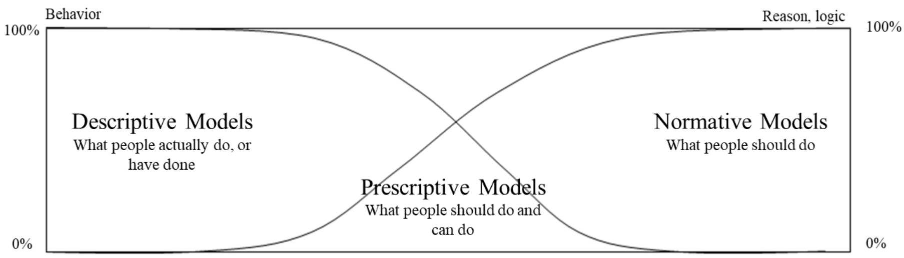

Figure 2-8 Decision models in a behaviour vs reason scale.

Although the descriptive theory has not constituted a factual challenge to normative theory by offering a general and compatible decision-making theory, it has been able to explain to some extent why people may deviate from rational behaviour. One principle is that people's set of beliefs or culture may influence and corrupt information processing (Oliveira, 2007).

A central distinction among different decision-making strategies (theories/models) is the extent to which they make trade-offs among attributes or not. In this case, we can distinguish between non-compensatory and compensatory strategies (Dillon, 1998). Non-compensatory strategies are based on the elimination of alternatives based on a single attribute comparison, (e.g. 0/1). These two strategies represent the same principles that the two evaluative criteria proposed by Beach and Mitchell (1987) in image theory, compatibility and profitability (see Section 2.1.6.1.6). On the other hand, in a compensatory strategy, the decision-maker will trade-off between a high value on one dimension and a low value on another dimension. For example, a lower cargo carrying capacity of a vessel may be compensated for by a lower newbuilding price. Descriptive models are generally non-compensatory while prescriptive and normative models are typically regarded as being compensatory. Similarly, the decision strategy can be alternative-based, by looking at particular alternatives across attributes, or attribute-based, by examining particular attributes across alternatives (Dhar, 1996). Utilizing these two aspects, the nature of processing and evaluation of information, Dhar (1996) proposes four decision rules, viz. additive difference, linear additive, lexicographic and conjunctive.

Another useful comparative measure of descriptive models involves determining whether they employ holistic or non-holistic strategies (Dillon, 1998) or whether they use an absolute or comparative approach (Shafir, Osherson and Smith, 1993). When relying on the pairwise comparison of alternatives (comparative approach), the attractiveness of an alternative will depend on the nature of the alternative it is being compared with, while on absolute approaches, the attractiveness of alternative is independent of the presence of other alternatives. The four strategies identified by Dahr (1996) are described as follows: (i) additive difference: the difference between two or more alternatives is defined as the sum of the pairwise comparison of each attribute. Thus, the alternative that has the highest positive difference is the best; (ii) linear additive: each attribute is given a weight reflecting its importance. The evaluation of each alternative is then the sum of the weighted values of all attributes. Thus, the alternative that has the highest overall value is the best; (iii) lexicographic: the evaluation between alternatives is based on the pairwise comparison of the most important attribute. If one or more alternatives are the best in that attribute, the choice among them goes to the next attribute in the hierarchy, and (iv) conjunctive: a minimum level is considered for each attribute, and the alternatives not fulfilling them are eliminated. Thus, the alternative fulfilling more attributes is preferred.

A practical case can be the selection of a vessel design alternative. Consider a shipowner interested in building a platform supply vessel (PSV) of 4 000 tonnes deadweight (DWT), 800 m^2 of deck area and fire-fighting capability. The shipowner would be faced with some alternatives like the ones presented in Table 2-2, which represent real vessels from recognized offshore vessel designers.

Table 2-2 Alternative designs of 4 000 DWT PSV vessels.

	Alternative 1	*Alternative 2*	*Alternative 3*	*Alternative 4*	*Alternative 5*
DWT (tonnes)	4 000	3 800	4 234	3 800	4 000
Deck area (m^2)	810	801	850	800	846
Crew (people)	30	25	24	26	26
NB price (mill USD)	43.0	44.6	44.3	47.5	37.2
FiFi (class)	1	1	2	-	1

Following a cognitive strategy, alternative 4 would be discarded, since it has not FiFi capability. Further, considering a cut-off of 26 crew and 45 mill USD, alternative 2 and 3 can be removed from the selection. The shipowner would have to choose between alternative 1 and alternative 5 since those are the only ones fulfilling the minimum requirements for all the attributes. If the shipowner rather considers a lexicographic strategy, where deck area is considered as the most important attribute, alternative 3 would be his choice. On a linear additive strategy, each attribute would be weighted based on its importance level, and the final choice would be made based on the total sum for each alternative. Alternative 3 would be selected, as it has the highest overall value. Finally, alternative 1 would be selected if the shipowner would have followed an additive difference strategy since that is the alternative with the highest positive difference.

The use of an adequate selection rule will influence the level of indecision the decision-maker will experience, impacting the likelihood of arriving at a decision or defer it. In Dhar's study, which consisted of students making ordinary purchasing decisions such as television, laptop or apartment, up to 40% of the decisions were deferred when using additive difference, it only happened in 14% of the cases when using a linear additive strategy. Lexicographic and conjunctive presented 19% and 32% regret rate respectively. One of his findings states that "when subjects are uncertain about which alternative to purchase, brands associated with higher values on the more important attributes are more likely to be selected than other alternatives with the same overall attractiveness" (Dhar, 1996, p. 280). This aspect relates to the uncertainty avoidance index (UAI) proposed by Hofstede (2001), who suggests that some people can cope well with uncertainty, while others need to rely on firm laws and norms to reduce the anxiety uncertainty produces on them. Cultural effects on how individuals support uncertainty and ambiguity are explored by Iyengar (2010).

This aspect of choice among alternatives brings us to a new perspective of uncertainty, the one generated by the indecision of which alternative to choose, and the effect that decision rules have on it. Although linear additive strategies, such as multi-attribute utility theory (MAUT), result in the highest rate of choice, decisions taken under time pressure tend to follow lexicographic strategies (Dhar, 1996). Because of the intransitivity present in real-life choices (Tversky, 1969), like choosing among alternative platform supply vessel designs, the use of non-compensatory strategies may present negative effects. A vessel alternative that was discarded in the first round of selections may be the preferred solution in further stages. This is also applicable in multi-stakeholder decisions as studied by Garcia *et al*. (2019), who identify how non-compensatory strategies may lead to overspecified designs.

There is no consensus with regards to which perspective, normative or descriptive, performs better under uncertainty conditions. Fredrickson and Mitchell (1984) identify a negative relation between rationality in decisions and outcome performance in uncertain environments. The relation was found positive in certain, or stable environments. Contrary, Dean and Sharfman (1996) found the opposite effects, with stronger positive effects of rational choice in uncertain environments than in certain ones. The results from both studies have been further supported subsequently by several authors. An example is the use of heuristics in decision-making situations under uncertainty, which may lead to better decisions than sophisticated normative models (Gigerenzer and Gaissmaier, 2011; Brighton and Gigerenzer, 2015). Intuition has become a widely used tool by decision-makers in uncertain situations when complete, accurate and timely information is not available. Still, there is not enough research proving its benefits towards outcome performance (Elbanna, 2006).

Elbanna (2006) collects an overview of studies on these topics and suggests seven possible reasons for these contradictory findings: (a) insufficient understanding of environmental variables, where only some environmental variables are considered; (b) cultural diversity, explaining that some models can be applied in some cultures and not in others; (c) lack of systematic categorization of process variables; (d) methodological differences, including data collection, sample size or type of industry; (e) differences on the operationalization of constructs, e.g. different constructs of rationality; (f) alternative levels of analysis, process vs outcome performance; and (g) lack of sufficient resources and information. In conclusion, there is not strong support for a normative either a descriptive perspective in decision-making under uncertainty.

2.1.6. Decision-making theories

Literature is abundant with decision-making theories, both on a theoretical level, but also with practical applications. Some of the decision theories have had more success and being implemented in many industries, while others have been relegated to only theoretical application and the less fortunate, have been broadly criticized and potentially not further developed. In this section, we make a literature review of some of the most recognized decision-making theories in the literature, with special emphasis on looking for their strengths and weaknesses towards handling uncertainty in ship design processes.

Overall, decisions are based on logical, conscious thinking, or the result of the judgment and intuition (Simon, 1987); or a combination of both. These two processes, logical and non-logical, relate to the two decision systems studied by Kahneman and Tversky (1974). Logical decision making, also described as normative, relies on explicit decision-making goals, and alternatives where the consequences of different decisions are assessed, calculated and evaluated before a final decision is made (Simon, 1987). On the other hand, non-logical decision-making (or descriptive theories) build on the intuition of the decision-maker to make a choice. Intuition relies on experts' professional judgment (Simon, 1987). Descriptive decision models are common from situations that have to be made under time pressure and where there is no time to evaluate all potential alternatives. In these situations, decision-makers rely on their intuition (experience) to make a choice. Although descriptive decision models are associated with irrational decisions, this conclusion is not completely true. Simon (1987) calls here for a distinction between expert judgment and emotion-driven intuition. The former is a judgment base on learning and experience, largely adaptive, while the latter is more rudimentary and pressure-driven process, more likely to involve biases and errors. Hence, an intuition based on expert judgment shall be rational, while an emotion-driven decision will, most likely, be an irrational choice (Simon, 1987). Notice that expert judgment is also subject to bias and errors (Taleb, 2010). Descriptive decisions are taken based on a set of assumptions. The conclusions taken shall be rational within that set of assumptions, but they may result irrational if those assumptions are not appropriate (Simon, 1987). These two thinking approaches have developed into two avenues of decision-making, normative and descriptive, and a third one merging both of them, a prescriptive approach. A similar exercise was carried out by Miller *et al.* (2002) who propose a categorization of these decision-making theories regarding two dimensions, action and interest. On the action perspective, the authors differentiate the cohesion of the decision-making, in regards to the sequentially and linearity of the process. Hence, decision-making theories are categorized on a scale from coherence to chaos. Similarly, the interest dimension differentiates between those theories focused on decision-making as a problem-solving activity and those negotiations where politics influence the way of how decisions are taken.

Although some authors like Christensen (2006) argue that normative models are more useful and advanced than descriptive models, it is perceived that managers and in general, decision-makers rely primarily on descriptive models (Turpin and Marais, 2004). Brunsson (2002) suggests three reasons as to why decision-makers do not rely [more] on normative models, basing their decisions mostly on [irrational] descriptive or prescriptive models: i) The complexity of models derived from operations research, decision-makers are not "clever enough" to practice normative models in their decisions; ii) the inherent irrationality of human beings; iii) practical restrictions given by lack of complete information or by quantities of information beyond decision-makers' capability. These elements contribute to the fact that managers and decision-makers find limited use for normative models in their everyday environments (Turpin and Marais, 2004). In the end, as Larichev puts it "To be socially acceptable, the decision method must be readily adjustable to the accepted way of discussing problems in a particular organization" (Larichev, 1999, p. 132), and decision-makers end up following different models as decision characteristics vary (Grandori, 1984). Stingl and Geraldi (2017b) suggest that the preference towards descriptive (or prescriptive) decision models builds on the increasing complexity and information demand of newer normative models; which have resulted in very specialized models requiring specific expertise and relying on black-box tools. Thus, uncertainty regarding what is going on inside the decision model limits its usability.

In the following paragraphs, we explore some of the most commonly used decision-making methodologies. The different methodologies are categorized in descriptive, prescriptive and normative models respectively. Each of the methodologies is related to its role in managing uncertainty in the decision-making process.

2.1.6.1. Descriptive Decision-Making Theories

The fact that actual decision-making behaviours deviate substantially from those described by normative, rational theories has spurred the development of behavioural decision-making theories (Stingl and Geraldi, 2017a), which explore the understanding of human beings in decisions. Powell *et al*. (2011) identify three schools of research within behavioural decision-making, named: reductionist, pluralist and contextualist. The three schools differentiate on the nature of the deviation from a normative *ideal*. Reductionists relate the deviation from rational choice to cognitive limitation (errors and biases). This school builds on the work of Tversky and Kahneman (1974). Similarly, pluralists suggest that such deviation from rational decision-making is the result of the conflict among decision-makers (lies or lack of trust). Contextualists, however, do not rely on a rational choice and focus on the process leading to a decision, and the context in which takes place (misunderstandings) (Stingl and Geraldi, 2017a). Each of these three schools evaluates the effects of one type of uncertainty, named error and bias, miscommunication and context, into the decision-making process. Stingl and Geraldi (2017a) found, based on a broad literature review, that techniques from the three schools are often used simultaneously, but critique the lack of commonality among them.

The following paragraphs include a short introduction to popular descriptive decision-making theories and relate their perception and consideration of uncertainty. Seven descriptive decision-making theories are here explored: (1) satisficing model, (2) garbage can, (3) naturalistic decision-making, (4) political view, (5) advantage model, (6) image theory, and (7) incrementalism.

2.1.6.1.1. Satisficing (or bounded rationality) model

The satisficing model relies on the assumption that decision-makers do not have perfect, complete information (bounded rationality), and therefore optimal decisions are not feasible.

Thus, the satisficing model relies on the intrinsic nature of uncertainty in decision-making situations. Decision-makers choose one alternative that satisfies some criterion or standard. Faced with the imperfectability of decision-making, satisfying models seek for ways to achieve, if not optimal outcomes, at least acceptable ones (Buchanan and O'Connell, 2006). The idea of satisfaction rather than optimizing was introduced by Simon (1978). The culture of satisficing applies to both, the amount of information available at the time of making a decision, and the quality of the outcome of that decision. Ship design relies, to a large extent, on a satisficing principle. Although ideally, stakeholders would desire a maximization of the performance relating to all the elements of a vessel, this is not always possible, as they are interconnected. For example, when designing a cargo-carrying vessel, the designer has to make a compromise between the cargo-carrying capacity of the vessel (increase the volume under the water) and reducing the fuel consumption of the vessel (reduce the volume under the water). Alternatively, the ship designer could consider reducing the speed of the vessel to minimize fuel consumption while maintaining high cargo-carrying capacity. Yet, this would reduce the cargo-carrying capacity of the vessel over time due to its lower speed.

2.1.6.1.2. Garbage can

The garbage can model represents decision-making as an *organized anarchy* where streams of problems, solutions and participants encounter each other for making a choice. The garbage can model highlights the fragmentedness and chaotic nature of decision making in organizations (Turpin and Marais, 2004); characterized by three principles (Cohen, March and Olsen, 1972): (i) problematic, inconsistent and ill-defined preferences, (ii) unclear technology, processes are not fully understood, and (iii) fluid participation, unclear role of decision-makers. In such situations, the intent and result of decisions are uncoupled, hence action would not lead to the expected outcomes (Miller, Hickson and Wilson, 2002) as it will be deviated by progressive actions. These situations are common in ship design processes, as described by Pettersen *et al*. (2018).

2.1.6.1.3. Naturalistic decision-making

Naturalistic decision-making pursues the understanding of decision-making in its natural context. One example is field theory. Its development goes back to studies of military operations during WWII carried by Kurt Lewin (1890-1947). Another application of naturalistic decision-making is Recognition-Primed Decision (RPD). Klein's (1999) model on RPD is based on the experience of the decision-maker and her capacity to recognize a situation as being similar to another of the past. Simon (1987) also identifies a recognition and retrieval process in descriptive decision-making. For his research, Klein studied life-or-death decision-making situations faced by firemen, doctors or soldiers, and finds that these experts take *recognition-primed decisions* on 80% of the cases (Klein, 1999, p. 24). By similitude of situations, it is possible to extrapolate goals, expectations, courses of action, etc. (Turpin and Marais, 2004). A ship designer, for example, would recur to previous projects of a ship type or of the same customer when considering approaching a new project. What was important for this vessel type? Or what did that customer put more interest in? This model can be useful in the situation of uncertainty, although the experience from similar projects of the past not always is representative for present situations. Recognition-primed decisions (RPD) consist of two processes: (i) recognise a situation, and (ii) identify a course of action. First decision-makers identify the situation and recognize it as typical and familiar. By recognising a situation as typical, they can also associate objectives, what type of information is important, and the typical ways of responding to it. Second, the decision-maker identifies a course of action likely to succeed (Klein, 1999). Case-based reasoning is another application of this principle that has been used as bases for artificial intelligence (Aamodt, 1993). Case-based decision-support systems assist decision-makers by comparing the specific decision situation with previous ones and consequently suggests actions with their predicted consequences (Aamodt, 1993).

2.1.6.1.4. Political view

The political view describes the decision-making process as a bargain driven by the self-interest of each of the decision-makers (Turpin and Marais, 2004). The decision relies here on the power and influence of each stakeholder (Pfeffer, 1992). In politics, for example, the choice should be made to favour the interests of the majority of the people. In decision-making situations with stakeholders that do not share common mental models, there is a risk of achieving irrational outcomes if one of them doesn't play a role of *dictator* (Hazelrigg, 1998; Broniatowski, 2017a). This is unlikely to happen is the stakeholders have a common understanding of the problem at hand (Richards, McKay and Richards, 2002). A political view would then be recommended in those situations. In ship design processes, the shipowner, as a customer, would play the role of dictator. A dominant decision-maker is preferred in times of uncertainty (Kakkar and Sivanathan, 2017).

2.1.6.1.5. Advantage model of choice

The advantage model of choice was proposed as a decision-making model for monetary lotteries (Shafir, Osherson and Smith, 1993); resulting from the fact that people in a decision such as a lottery, violate the axioms of utility theory. Advantage theory was developed as an alternative descriptive theory to decision-making in risky and uncertain environments (Shafir, Osherson and Smith, 1993). This model assumes that people making decisions regarding lotteries consider the individual comparison of options in terms of gains and losses. It is argued that the model captures the behaviour of human choice in risky situations.

The advantage model consists of a partially comparative model, where it is assumed that the attractiveness of an option depends on the alternatives it is compared to. This quality differentiates it from prospect theory, which follows an absolute approach where the attractiveness of one alternative is independent of the nature of the other alternatives. One could argue that this is the situation in most ship design processes, especially those relying on a tender process. In this decision situation, the entity issuing the tender has to choose among the given alternatives.

2.1.6.1.6. Image theory

Image theory is a schema theory which relies on the assumption that information is represented for decision-makers as images (Beach and Mitchell, 1987; Beach, 1993), including choice strategy, goals and the role of the decision-maker in the process. Beach and Mitchell (1987) identify four images: self-image, trajectory image, action image, and projected image, each with a different type of information. The self-image represents the beliefs and values of the decision-maker, also called principles. These principles are the bases to define the goals and objectives of the decision-maker, registered as the trajectory image – where to go? The plans and subsequent tactics are defined as the action image. The fourth image, the projected image, consist of the foreseen events and states resulting from the actions taken or the absence of those.

In image theory, we can distinguish two types of decisions: adoption and progress decisions. Decisions are made following two types of tests, compatibility or profitability tests (Beach and Mitchell, 1987; Beach, 1993). Adoption decisions consist of the adoption (or rejection) of candidates (goals, objectives, plans and tactics) for the trajectory and strategic images. Thus, goals and objectives must be compatible with decision-makers principles and other goals and objectives. Plans and tactics must promise the fulfilment of a specific goal without interfering other goals and objectives. Candidates not fulfilling these two tests are eliminated (Beach, 1993). Progress decisions consist of the comparison of the trajectory image and the projected image. Is the development of the selected plans and tactics in line with expectations? If not, something must be done to rectify the progress, either select a new candidate or correct the existing tactics and plans (Beach and Mitchell, 1987). There is not a clear description of what is the role of uncertainty in image theory.

2.1.6.1.7. Incrementalism (or successive limited comparisons)

In his article, *The Science of Muddling Through*, Lindblom (1959) described the difficulty of solving complex problems on a rational form. Lindblom suggests that the bounded rationality characterizing human decision-makers leads in most of the practical cases to alternative ways of making decisions. His incrementalism theory consists of the comparison of a limited number of alternatives (selected based on experience and proximity) based on a short-list of selected goals (Lindblom, 1959; Lasserre, 1974). In general, the incrementalism method could be seen as a variant of the satisficing model, as it does not attempt for total comprehensiveness (Lasserre, 1974). As argued by Lindblom (1959, p. 88), "under this method, […] policies will continue to be as foolish as they are wise"; considering that neither all the goals nor choice alternatives are evaluated. Yet, it offers a realistic analytical framework to cope with social activities in complex environments (Lasserre, 1974). This theory proposed by Lindblom also recognizes the intrinsic nature of uncertainty and suggest accepting it and make decisions recognizing the limitation of imperfect information.

2.1.6.2. Prescriptive Decision-Making Theories

Prescriptive decision models are developed with the objective of eliminating the gap between normative and descriptive models. They ought to define what people should do and can do, by adapting normative models to human behaviour. The following paragraphs include a short introduction to popular prescriptive decision-making theories and relate their perception and consideration of uncertainty. Three prescriptive decision-making theories are here explored: (1) prospect theory, (2) contingency theory and (3) adaptive heuristics

2.1.6.2.1. Prospect theory

Prospect theory is seen as the result of the weakness of expected utility theory to represent an individual choice in risky situations. It was initially introduced by Kahneman and Tversky (1979) and later expanded by the same authors to cater to cumulative decision weights as opposed to the initial model (Tversky and Kahneman, 1992). Prospect theory integrates the differences in perception of gains and losses through the concavity and convexity of the value function together with the nonlinearity of the probability scale (Kahneman and Tversky, 1979). Prospect theory was initially limited to risky situations with a limited amount of outcomes, but it has been later further expanded to uncertain situations with a broader set of outcomes (Tversky and Kahneman, 1992). The newer cumulative prospect theory combines the cumulative model proposed by authors like Quiggin (1982), with the behaviour regarding losses and gains from the older prospect theory. In classical utility theory, the utility of an uncertain event is calculated as the sum of individual utilities weighted by its probability of occurrence. In cumulative theory, however, the individual utilities are related to the final consequences, gains or losses, rather than to the assets. The weights are also decoupled from the individual probabilities since the model evaluates the entire cumulative function (Tversky and Kahneman, 1992).

2.1.6.2.2. Contingency theory

Contingency theory, proposed by Lawrence and Lorsch (1967), became very popular in organizational studies for organizations operating in uncertain environments (Grandori, 1984). Contingency theory asserts that there is no one best way to make a decision or handle a process, as this will be influenced by both internal and external factors (Lawrence and Lorsch, 1968). Earlier, Thompson and Tuden (1959) developed a contingency framework for decisions under uncertainty relying on two uncertainty dimensions: (i) uncertainty relating to the cause-and-effect relations, and ii) uncertainty about preferences. The latter can be a consequence either of a conflict among clear divergent interests or the lack of clarity about stakeholder's preferences (Grandori, 1984).

Thompson and Tuden (1959) propose four non-mutually exclusive strategies depending on the level of uncertainty of these two dimensions, as presented in Figure 2-9. If both, cause-and-effect relations and preferences are clear, a computational strategy should be chosen. However, if both are uncertain, an inspirational strategy is recommended. For a situation with clear relations but unclear preferences. A compromising strategy prevails, while a judgmental strategy is recommended in situations with clear preferences but uncertain relations (Grandori, 1984). These fours strategies combine decision-making models from five decision theories, viz.: optimizing, heuristics, incrementalism, cybernetic and random choice. The decision-maker role is then to classify the state of uncertainty, eliminate those uncertainties that are not feasible and select the most viable strategy to his or her problem, considering time and resources availability and importance of the decision (Grandori, 1984).

In a ship design decision-making process we can find examples of these four types of decisions. Consider, for example, the stability calculation of a vessel. Both, preferences and cause-and-effect relations are known. The former is given by classification rules and IMO requirements, while the latter is given by physical principles. In this case, the selection criteria should follow a computational strategy. But to select the most appropriate hull for a given vessel design, however, the design process should follow a compromising strategy. In this situation, cause-and-effect relations are also defined by physical principles, however, the preference of speed is not that clear, and the designer has to compromise the need of speed and the consequent power requirement. Similar examples can be found for situations where cause-and-effect relations are unknown.

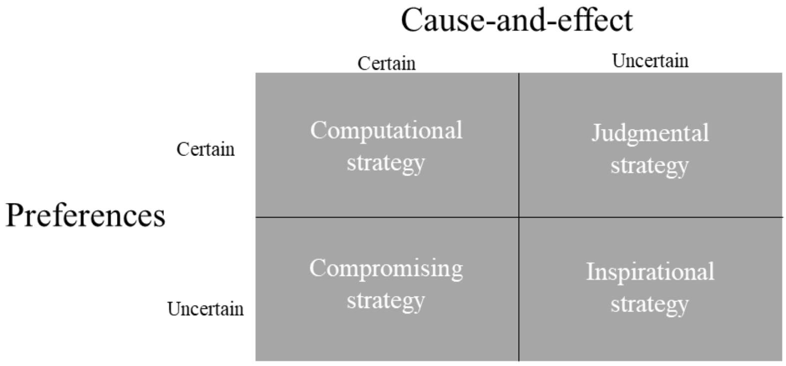

Figure 2-9 Categorization of uncertainty handling strategy by preferences and cause-and-effect factors.

2.1.6.2.3. Adaptive heuristics

Adaptive heuristics builds on the concept of bounded rationality proposed by Simon (1978). Multiple researchers have found evidence showing that decision-making in real-life relies on biases and heuristics (Tversky and Kahneman, 1974). Adaptive heuristics is proposed, by the literature, as a decision-making alternative in decision-making situations characterised by uncertain environments, where the availability of information is limited. Similarly to intuitive reasoning, adaptive heuristics builds on expert knowledge and group decision-making to turn tacit knowledge into explicit (Stingl and Geraldi, 2017b). Heuristics rely on simplification, they work as effective cognitive processes ignoring, consciously or not, part of the information (Gigerenzer and Gaissmaier, 2011).

Heuristics is common in the ship design industry, especially when it comes to marketing strategies of newbuilding projects. When marketing new vessel designs, ship design firms select a limited number of shipping companies to which their design may be of interest. To carry out this exercise, they recur to multiple heuristic strategies. One example is the assumption that previous customers will repeat (historical customers), or consider that companies order vessels on a periodic basis (periodic behaviour), or that those who have historically focused on 2nd hand tonnage, will continue to do so (historical strategy). Another example is in the evaluation of shipbuilding capacity. Rather than evaluating each individual shipbuilding facility, their organization and their capability to build; it is common to consider as active shipyards those with vessels in their orderbooks, regardless of their capacities and capabilities.

The goal of introducing heuristics in decision-making is to make decisions as accurate as with normative models but carried out more quickly (Gigerenzer and Gaissmaier, 2011). Over the years, several have been the adaptive heuristic strategies proposed and tested by researchers in descriptive and prescriptive decision-making. Table 2-3, provides an overview of nine heuristic strategies, including a brief description of their principles. However, it remains unclear when and how each of these strategies should be used.

Heuristics may result in poor decisions if they are not utilized in the right environment or for the right decision problem. Thus, it is important to understand when and how each heuristic strategy can be used. This is the field of study of ecological rationality (Neth and Gigerenzer, 2015). With the intention of guiding decision-makers on what strategy to use in a given problem, researchers have proposed different ways of categorizing decision problems and correlating them to different heuristic strategies. One example is the categorization proposed by Stingl and Geraldi (2017b), who differentiate decision situations based on the type of uncertainty and the decision task. Their categorization is used to correlate the nine heuristic strategies summarized in Table 2-3 with different decision situations. In absence of experience to guide decision-makers on the selection of a proper heuristics strategy for each decision situation (Gigerenzer and Gaissmaier, 2011), they may rely on this and other categorizations.

Table 2-3 Nine examples of adaptive heuristic strategies. Adapted from (Stingl and Geraldi, 2017b).

Adaptive heuristic	Definition	Type of uncertainty	Decision task
Recognition heuristic	If one of two alternatives is recognized, infer that it has a higher value on the criterion.	Knowable uncertainty	Judgment
Take-the-best	To infer which of two alternatives has the higher value, go through cues[3] in order of validity until there is a cue that discriminates the two alternatives, then pick the alternative this cue favours.	Knowable uncertainty	Choice
Tallying	To estimate a criterion, do not estimate weights but simply count the number of positive cues.	Knowable uncertainty	Choice
Satisficing	Search through alternatives and choose the first one that exceeds your aspiration level.	Unknowable uncertainty	
Imitate the majority	Consider the majority of people in your peer group and imitate their behaviour.	Unknowable uncertainty	Choice
Fast-and-frugal-trees	Skimmed down decision-tree with each node connecting only to one further node and an exit.	Knowable uncertainty	Judgment
Fluency	Alternatives that are processed more fluently, faster, or more smoothly than others are preferred.	Knowable uncertainty	Judgment
Similarity	Associate the current decision situation to a similar situation in the past.	Knowable uncertainty	Judgment
Tit-for-tat	Cooperate first, then imitate your partner's most recent behaviour.	Unknowable uncertainty	Choice

[3] Cue: A circumstance or piece of information which aids the memory in retrieving details not recalled Choice spontaneously (Oxford University Press, 2016).

2.1.6.3. Normative Decision-Making Theories

Normative decision theories define the principles that decision-makers ought to follow on the making of decisions. It is the study of guidelines for the right action (Fishburn, 1995). Normative decision-making relies on rationality. Rationality has been defined as the compatibility between choice and value. The rational decision-making view assumes a rational and completely informed decision-maker (economic man) (Turpin and Marais, 2004). Rational behaviour seeks to optimize the value of the outcomes focusing on the process of choosing rather than emphasizing the selected alternative (Oliveira, 2007). However, people rarely adhere to logical models of choice.

The following paragraphs include a short introduction to popular normative decision-making theories and relate their perception and consideration of uncertainty. Two normative decision-making theories are here explored: (1) utility theory and (2) game theory.

2.1.6.3.1. Utility Theory

Utility theory can be rooted back to the late 1700s, with the publication of *The Theory of Moral Sentiments* by Adam Smith (1723-1790). Smith proposed differentiation between the value in use, as the utility of a particular object, and value in exchange, as the economic value of that particular object (Smith, 1759). Anecdotally, objects with high value in use have low value in exchange and vice-versa (Stigler, 1950). Smith's concept of value in use was further developed by Jeremy Bentham (1748-1832), who characterises it as "the degree of intensity" possessed by the use or ownership of an object (Stigler, 1950). The goal of the decision-maker is then to maximize such a degree of intensity (Read, 2004). Soon, researchers found the complexity of measuring a term, utility, which was different for each person, and which marginal utility could decrease as quantity increased (Stigler, 1950). Aggregation of utilities was also discussed during the early days of utility theory, concluding that the total utility of two commodities together is not necessarily equal to the sum of the total utilities of each separately (Stigler, 1950). Many researchers have argued the fact that utility theory does not properly combine the preferences of groups (Fitzgerald and Ross, 2014).

It was a few years after when von Neumann and Morgenstern (1944) suggested that in order to establish a logical utility function, decision-makers should follow a series of logical principles (axioms). The utility function would then represent the preferences of the decision-maker and become decoupled of more subjective terms like experience or satisfaction (Read, 2004). It was argued that subjective experience could not be measured or observed and that the utility of the outcomes expressed indirectly the experienced utility of rational decision-makers (Kahneman, Wakker and Sarin, 1997). Expected utility theory (EUT) has since its initial proposal been extensively used in decision situations with risky or uncertain contexts. It consists of the comparison of the individual expected utility values for each decision alternative (Mongin, 1998). The model assumes that the decision-maker has a complete and transitive preference in choices (Lattimore and Witte, 1986).

Generalizations of this theory are the so-called, anticipated utility theory or subjective expected utility theory. Anticipated utility theory (AUT) proposes an adaptation of expected utility theory, considering the challenges relating to Axiom 4 (see (von Neumann and Morgenstern, 1944)) of the irrelevance of independent alternatives, where decision weights are substituted by probabilities (Quiggin, 1982). Similarly, the subjective expected utility theory (SEUT) was first proposed by Savage (1954) as a generalization of expected utility to decisions under uncertainty, where probabilities could not be described objectively.

Considering the measurement challenges that the utility theory proposed by the early utilitarian philosophers, Kahneman, Wakker and Sarin in 1997 proposed the concept of *experienced utility* (Read, 2004). Experience utility, as opposed to *decision utility* (which represents the axiomatic approach of expected utility) derivates from Bentham's work. Expected utility is based on the assumption that "the functions that relate subjective intensity to physical variables are qualitatively similar for different people" (Kahneman, Wakker and Sarin, 1997, p. 380) , or in other words "there is a measurable good that is separable from the choices people make" (Read, 2004, p. 6). Experience utility (total utility) and decision utility do not have to coincide necessarily, as Kahneman *et al*. (1993) demonstrate. One reason for this is the fact that decision utility, presumably a result of remembered utility, it is a biased reflection of total utility. This interpretation could explain the behaviour of shipping companies with regards to vessel speed, guided by fuel prices in the short-term rather than considering the total life-cycle of the vessel (Kalgora and Christian, 2016).

2.1.6.3.2. Game theory

Game theory was first proposed by von Nuemann and Morgenstern (1944) in their book *Theory of Games and Economic Behavior*. The initial goal of game theory was to focus on situations where two or more individual had an exchange of goods or services and each of them pursued the maximization of his or her utility. These games are known as zero-sum games and pursue the identification of an equilibrium point. The latter assumption has been further expanded to non-zero-sum games. Game theory has been applied to both, cooperative games (Nash, 1953), where it is assumed that the individuals in the game can achieve a rational joint plan of action, and non-cooperative games (Nash, 1951), where there is no communication between the individuals involved in the game. Cooperative situations can be seen as a special case of non-cooperative games. Nash suggests that cooperative games can be modelled as the search of a "suitable, and convincing, non-cooperative model for negotiation" (Nash, 1951, p. 295). A classic example of problem-solving with game theory is the Prisoner's dilemma. This game represents contraposition between individual rationality (selfish behaviour) and group rationality (collaboration). The game is characterized by dynamism, so the result of the game will depend on the reaction of the two prisoners. The uncertainty regarding the behaviour of the other party provides incentives for selfish behaviour, while the best outcome would be achieved if both parties cooperate (Axelrod, 1980).

The use of game theory has been rather limited for practical, industrial applications, while it has been broadly applied in theoretical environments. One challenge is the complexity of the mathematical work required, which for making feasible the resolution of real-life problems would require the use of approximate computational methods (Nash, 1951).

A summary of the decision-making theories reviewed in this section is included in Table 2-4.

Table 2-4 Summary of decision-making theories.

	Decision theories	*Ref. publication*	*Handling of uncertainty*
Descriptive models(Pfeffer, 1992)	Satisficing model (or bounded rationality)	(Simon, 1978)	Accept the limited availability of information and capacity to process it
	Garbage can	(Cohen, March and Olsen, 1972)	Handling stakeholders' expectations
	Naturalistic decision-making	(Klein, 1999)	Use experience from the past
	Political view	(Pfeffer, 1992)	A dominant decision-maker
	Advantage model	(Shafir, Osherson and Smith, 1993)	Individual comparison of gains and losses
	Image theory	(Beach and Mitchell, 1987)	Unclear position with respect to uncertainty
	Incrementalism	(Lindblom, 1959)	Simplified list of alternatives and goals
Prescriptive models	Prospect theory	(Kahneman and Tversky, 1979)	Weighted gains and losses
	Contingency theory	(Lawrence and Lorsch, 1967)	Different decision strategies depending on the type of uncertainty
	Adaptive heuristics	(Tversky and Kahneman, 1974)	Simplification of the decision problem
Normative models	Utility theory	(Smith, 1759)	Decisions are based on the utility of each alternative
	Game theory	(von Neumann and Morgenstern, 1944)	Decision-makers pursue maximization of utility

2.1.7. Exploration vs exploitation

The balance between exploration and exploitation of knowledge in decision-making situations has been deeply studied over the past 25 years (March, 1991). His article expands on the relation between the exploration of new possibilities and the exploitation of well-known alternatives. Designers have to decide whether to spend their time exploring unfamiliar areas or contrary on exploiting their knowledge and resources. We may relate this to the decision of starting a design from scratch or using a standard vessel design, based on existing designs. The balance of exploration and exploitation activities in ship design is paramount for the success of the design firm, as this has to be traded off with the risk of losing the contract (Erikstad, 2007). One may argue that by relocating more resources to the exploration phase, designers will delay their response to the customer and, therefore, reduce its impact and attractiveness to the customer. The same could result in spending little time on exploration and offering a standard solution. Thus, choosing can become a lose-lose situation (Iyengar, 2010). Iyengar argues that decisions made under an uncertain or weak exploration of choice options could be regretted later on (what if?).

The overall conceptual ship design process could be looked upon as two overlapping processes leading to the definition of the final conceptual vessel design. Firstly, a managerial process of defining a set of requirements, hence exploration, and secondly, an abductive process of finding a technical solution matching those, hence exploitation. These two processes relate to the three elements of decision making proposed by Skinner (2009): what we want? what do we know? and what we can do about it? In Figure 2-10, the exploration and exploitation phases are related to the traditional stages of a ship design process. The figure outlines the design efforts relating to each stage of the design process in terms of man-hours, and it represents our experience at Ulstein with offshore vessels. On a typical design process for a new offshore vessel concept, around three hundred hours are spent in the concept development phase, most of them relating to the definition of the technical solution. The first two stages, problem awareness and problem diagnosis are often discarded in many ship design processes (as exemplified in term of design effort in Figure 2-10). Thus, in many cases, ship designers rely solely on the tender requirements and the specification of the design given by the shipowner. This is reflected in most of the ship design literature, which considers exploration the assessment of potential design solutions within a design space (Papanikolaou, 2010). Exploitation is seen, on the other hand, as the detailed design phase, where designers look to exploit at the maximum the resources of a given conceptual design. Other authors (Meek, 1970) relate exploration to the market-oriented assessment of requirements, traditionally carried out by the ship owners.

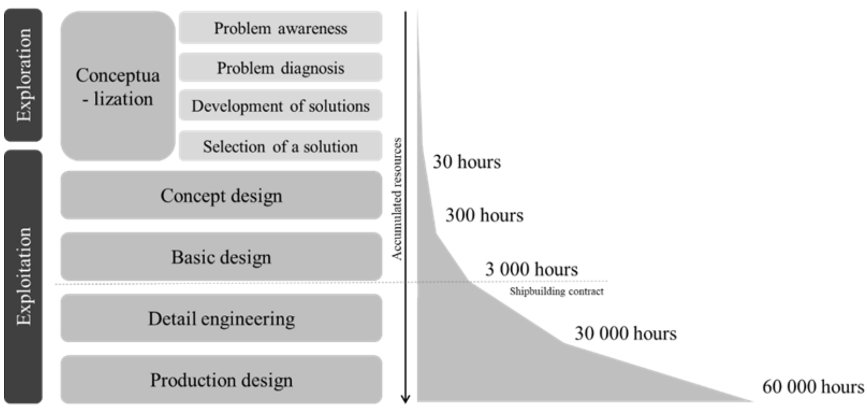

Figure 2-10 Ship design process – stages and resource intensity allocation (Garcia, Erikstad and Brett, 2019).

In today's competition, ship designers require shorter response time, more accurate responses and broader exploration of potential alternatives (Bonabeau, 2009; Ulstein and Brett, 2012). The fact that lead time is a major source of competitive advantage in design (Smith and Eppinger, 1998), urges ship designers to start drawing lines. A reason for this is that many do not understand a discussion on ship design without a general arrangement (GA) or a power curve at hand. The same could result in expending little time on the exploration and the offering of a product that does not fulfil the real needs of the customers. Thus, designers have to decide whether to spend their time exploring the problem and potential solutions for it or on designing a vessel based on the, very often unclear, predefined understanding of the problem. At this stage, it is also necessary to decide whether a completely new concept has to be developed (higher design uncertainty) or an existing design can be reutilized (lower design uncertainty). Before making these decisions, the ship designer should answer questions like: how well do we understand the operation of the vessel? Are there special features in that operating region? How does the vessel operator utilize the vessel? Considering that the most important decisions, those taken during the conceptual design phase are based on the weakest knowledge about the problem and the design itself; it is of interest for the ship designer to make available more information at the earlier stages. So, how can we find a better balance between problem identification and solution development in ship design? As both activities, exploration and exploitation, compete for scarce resources, design companies have to define better specific strategies to distribute and allocate resources (March, 1991).

Exploration is described by Lyles (1981) as the act of searching for information and evaluating the implication of alternative views to the problem. The availability and quality of relevant case information are the basis for good decision-making (March, 1994). Hence more information should result in better decisions. Unfortunately, the time and resources spent gathering extra information have an associated cost, which typically increases progressively with the amount of information collected (Samset, 1998). In general, strategies for resource allocation between exploration and exploitation activities rely on a way of weighting the value of information (VOI) (Rothschild, 1974; Tolpin and Shimony, 2012). The dilemma of deciding the stopping point for exploration activities has been explored by researches on economic (Cortazar, Schwartz and Casassus, 2001), decision-making theory (Garcia, Calantone and Levine, 2003) or management literature (Miller and Martignoni, 2016), both following deterministic and nominal principles. One of the main articles of this thesis focuses on this topic and exemplifies the use of value of information in conceptual ship design processes (Garcia, Erikstad and Brett, 2019).

2.1.8. Design as a decision-making activity

The principal role of a designer (or an engineer doing design work) is to make decisions (Bras and Mistree, 1991). Design is defined, from a generic perspective, as "to decide upon the look and functioning of (a building, garment, or another object), by making a detailed drawing of it"; "do or plan (something) with a specific purpose in mind" (Oxford University Press, 2016). Reviewing some of the principal publications on design theory – engineering design theory in particular – over the past 40 years (Archer, 1969; Coyne et al., 1990; Suh, 1990; Pahl et al., 2007), there seem to be in agreement on two basic principles of [engineering] design: i) it is a process involving decision making, and ii) it is a purposeful activity, motivated by the satisfaction of some needs or expectations. In general, design engineers view design as many different activities and purposes: An optimization, a process of drawing, as a creative process or a decision-making activity (Hazelrigg, 1997). Summarizing, engineering design can be described as the act of determining all possible design options and choosing the best one (Hazelrigg, 1998).

Design (as a decision-making process) can be described as a process that involves "a series of interrelated operations that are driven by decisions" (Girod *et al.*, 2003, p. 1215). The design process can be divided into four steps: problem definition, creative process, analytical process and ultimate check (Suh, 1990). Similarly, Coyne, *et al*. (1990) describe the process in three steps: Analysis, synthesis, and evaluation. These stages of design as a decision-making process show a clear differentiation with the traditional consideration of design as a problem-solving process. This traditional categorization of design as problem-solving activity (popular during World War II) relied on the fact that product specifications were provided by the customers (Hazelrigg, 1998) therefore, no problem definition activities were taking place. Ambrose and Harris (2010, p. 10) for example, define design as "a process that turns a brief or requirement into a finished product or design solution", although the authors recognise a "definition" phase where the problem at hand is formulated. More recently Hatchuel, *et al*. (2018) suggest that design has some of its roots in formal models of decision-making, problem-solving, and combinatorics. Decision-based design (DBD) is a representative methodology which reflects design as a decision-making process (Gurnani and Lewis, 2008).

However, design theory cannot be restricted to problem-solving alone (Hatchuel, 2002). Creativity plays also an important role (Suh, 1990) since it is responsible for the generation of alternatives. The effectiveness of design will then rely on the combination of the effectiveness of the decision-making process (Girod *et al.*, 2003) and the effectiveness of the creational process (Alexander, 1982). If the selection of the problem is poorly handled, the creational process will be constrained, and the number of potential alternatives to select among will be very limited. In this respect, both, decision-making and creativity have to be properly integrated. A similar conclusion is extracted from the work of Simon (1996), who investigates design through the lenses of decision-making and problem-solving paradigms. On the other hand, Hatchuel, *et al*. (2018) suggests that design presents a different capability, neither decision nor creativity, which they name generativity. Generativity is defined as the "Capacity to generate new propositions that are made of known building blocks but are still different from all previously known combinations of these blocks" (Hatchuel *et al.*, 2018, p. 9). In this line, Cross (2018a) suggests that a designer should have some special capabilities, *design ability*, which enhances the way he or she resolve ill-structured problems. His definition of design ability relies on the use of cognitive strategies, on a solution-focused perspective. An important conclusion from his work on design ability and subsequent *design thinking* is that they are abilities that can be trained and developed (Cross, 2018a).

Engineering design has been described as a process where information in the form of requirements is converted into the description of a technical system (Hubka and Eder, 1987), that must satisfy a given set of constraints (Coyne *et al.*, 1990). Yet, a good design fulfilling the requirements may fail to cover the needs it was designed for. In other words, the design would fulfil its function but not its purpose (Cascini, Fantoni and Montagna, 2013). An advanced well intervention unit may fulfil the well intervention function but fail to fulfil the need of providing affordable well-intervention operations. This characteristic of design suggests that the performance of the design process and the design product are not only a result of the mapping between functions and the attribute (*synthesis* process (Coyne *et al.*, 1990)) but also on the understanding of the problem (*analysis*). Although this process is critical, many design processes, mostly those based on a problem-solving view of design, do not present a formal distinction between needs and requirements (Cascini, Fantoni and Montagna, 2013). And in many practical cases, stakeholder expectations are taken as requirements and constraints, without questioning their validity, which may lead to ineffective design processes and products. Vermaas (2013) recognises this practice, where designers *bypass* some of the conceptual layers of the design process.

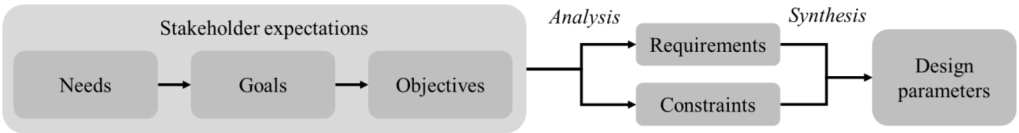

Figure 2-11 Design mapping process: needs – requirements – design parameters.

A generic design process is illustrated in Figure 2-11. *Needs* are the basic motivation for pursuing a change and define the problem we are trying to solve. This is what makes design a purposeful activity (Coyne *et al.*, 1990). They describe a benefit to be fulfilled, and not a potential solution nor physical measurements (Griffin and Hauser, 1993). In addition to needs, customers or users may specify a set of *goals*. Goals represent a desire, an expectation on what it has to be done in order to meet those needs, which doesn't have to be necessarily on a quantifiable or measurable form. Customer needs may be further complemented with *objectives*, which are specific target levels of outputs the design must achieve. For example, a need can be to provide weekly deliverables of a variety of products with a vessel, which can be supported by a goal such as to supply an offshore platform with its consumables. This need and goal can be complemented by an objective like supplying 5 000 tonnes of cargo per week. The combination of these three elements: needs, goals and objectives, is defined as customer expectations, and contrary to requirements, are not contractual (Hirshorn, 2016). Customer expectations can be explicitly communicated to the designer (e.g. a tender specification document), or it may be depicted by the designer based on the observation of customer's behaviour, his or her experience and know-how (e.g. a market research) (Bailetti and Litva, 1995; Cascini, Fantoni and Montagna, 2013). Notice that needs refer to outcomes, while objectives relate to outputs.

Functional *requirements* (FR) are the designer's characterization of the perceived needs for a product, and as their name indicates, are defined in the functional domain, in terms of a specific requirement (Suh, 1990). These functional requirements are designer's interpretation of customer's expectations (needs, goals and objectives) and are used as basis to define a physical embodiment characterised in terms of design parameters to satisfy these (Suh, 1990). The objectives proposed by the users (expectations relating to the output) can help the designer on the definition of the final functional requirements, although these objectives need to be feasible before a set of requirements can be defined. In many cases, the establishment of an acceptable (or correct) set of functional requirements may require an iterative process (the objectives proposed by the customer may not fulfil his/her needs). The definition of the functional requirements building on needs, goals and objectives provide a mechanism to ensure that all the stakeholders involved in the decision-making problem have a common understanding of the problem at hand (Walden *et al.*, 2015; Hirshorn, 2016). Topcu and Mesmer (2017) suggest that initializing design negotiation with given stakeholder requirements implies that design starts from a reduced design space, compared to the space of all technically feasible solutions. A good design should be designed based on the minimum set of requirements that characterises the needs of the customer. Some designers add additional functional requirements (FRs), overdesigning the products, which may result in costlier and less reliable products (Suh, 1990).

The use of needs as bases to specify the functional requirements in design processes is typical of innovation projects. Contrary, on engineering design problems where the objective is to improve or adapt existing designs, it is common that the designer specifies the set of FRs based on customer attributes and customer perceptions (objectives). In these cases, the needs are defined based on a preconceived physical solution, as they pursue the improvement of an existing design. This practice, as described above, may lead the ineffective design processes and resulting products.

It should be noticed that design literature is also lacking a uniform definition for the term function, which may be the result, or the reason, for the unprecise use of the term requirements. Eisenbart, Gericke and Blessing (2017) suggest that design literature and practitioners make use of several concepts of function. Up to 18 definitions were identified by Erden *et al*. (2008). These definitions have been grouped by Vermaas (2013), who propose three notions for function: (i) intended behaviour of devices, (ii) desired effects of the behaviour of devices, and (iii) the purpose for which devises are designed. However, the ambiguity created by the multiple meanings of the word function may have positive results in practice (Vermaas, 2013). Studies show that design practitioners switch between the different notions of function on their projects (Eisenbart, Gericke and Blessing, 2017), which shows the flexibility required in design methodologies.

In addition to functional requirements, designers have to specify *constraints*, which often have a limiting effect on the design. Contrary to functional requirements, constraints do not have tolerances (Suh, 1990). They represent the bound on an acceptable solution and can depend on the other constraints or functional requirements, whereas functional requirements cannot. They can relate to the design specification – input constraints - (eg. minimum deadweight) or to the system in which the solution must function - system constrains - (eg. monohull vessel) (Suh, 1990).

Design researchers have developed, over time, methodology describing how designers think and work, known as *design thinking* (Cross, 2008). Design thinking is view as a form of intelligence, which can be trained and developed (Cross, 2018a). As such, expert designers have the ability to deal with practical situations of uncertainty, inadequate information and unclear goals, making them capable of handling ill-structured problems (Cross, 2018a). This ability results on expert designers spending less time on problem definition, with controversial results.

2.2. Uncertainty in decision-making problems

Although policy-makers, designers, scientists and in general decision-makers would like complete certainty regarding the outcomes of their actions (Thissen and Agusdinata, 2008), a large number of problems, including ship design (Puisa, 2015b), require that decisions have to be made in the presence of uncertainty (Sahinidis, 2004; Bradley, 2012; Negulescu, 2014; Kochenderfer, 2015). This is characteristic of complex systems, where part of the uncertainty is inherent in the system and cannot be avoided nor eliminated (McDaniel and Driebe, 2005); which increases the difficulty of making a decision (Simon, 1987). Dowley and Slocum (1975) relate the intrinsic nature of uncertainty to the infinite terms of reality and the limited capacity of human beings to process information, also named bounded rationality (Simon, 1978). The inherent nature of uncertainty is also the reason why many decisions have to be taken. For example, Minsky (1982, p. 35) suggests that "underlying all financing contracts [decisions] is an exchange of certainty for uncertainty".

While research on decision-making under uncertainty have focused either on equivalent to certainties, such as market outlook, expected value or prognoses, or on rules for living with uncertainty, such as game theory, real options theory or scenario planning; business decisions and practitioners avoid uncertainty (Cyert and March, 2002), mostly by simplification of the problem building on heuristics (Tversky and Kahneman, 1992). Social psychology research finds that when making a decision under uncertainty, people look to peers for the guidance of how to proceed (Collins and Hansen, 2011). Many companies reduce the effect of uncertainty in their business activities by focusing on short-run decision rules, with a focus on agility and flexibility, and on utilizing negotiated environments. The latter aspect is widely expanded and recognized as a strategy to reduce environmental uncertainty. As an example, many shipping companies sign long-term deals with fuel suppliers to reduce the effects of uncertainty in their operations (Alizadeh and Nomikos, 2009) or signing long-term contracts on regardless of potentially lower dayrates.

Increasing attention is paid to the theme uncertainty in latest years (Perminova, 2011; Saunders, Gale and Sherry, 2013b; Erikstad and Rehn, 2015), from management, to design, communication, research, etc. comprising different industries and fields of knowledge: offshore oil & gas (OO&G) (PSA, 2016), nuclear power (Saunders, Gale and Sherry, 2013b), shipbuilding (Antunes and Gonzalez, 2015), ship design (Erikstad and Rehn, 2015), politics (Thissen and Agusdinata, 2008; Van Den Heuvel, Alison and Power, 2013), strategy (Walker, Haasnoot and Kwakkel, 2013), energy, mining (Cortazar, Schwartz and Casassus, 2001), investment (Majd and Pindyck, 1987), science (Pirner, 2015), project management (Ramasesh and Browning, 2014), business development (Müllner, 2016) and research (Peace Cox, 1974). Special interest is getting attention in safety-critical project-based industries, such as nuclear power plants or offshore platforms; industries historically focused only on risk-management procedures (Saunders, Gale and Sherry, 2013b; PSA, 2016). Because of its importance on the performance of companies, uncertainty management is considered one of the nine principles characterizing smart organizations (Matheson and Matheson, 2016).

Uncertainty is an inherent part of decision problems (Atkinson, Crawford and Ward, 2006; Saunders Pacheco do Vale and Monteiro de Carvalho, 2014), and typically increases with the complexity of the problem at hand (Peace Cox, 1974; Perminova, 2011). Considering multiple alternatives in decision problems evokes uncertainty, and uncertainty reduces motivation and commitment, two of the three factors needed for decisions to initiate actions (Brunsson, 2002). Uncertainty is, in most of the cases, measured through a binary lent in decision-making problems, where decisions are taken based on pure bets – where it is assumed that there is not uncertainty, or never-ending up with a decision – where uncertainty is the dominant concern (Wernerfelt and Karnani, 1987; Courtney, Kirkland and Viguerie, 1997). Neither one of those extremes is recommended. Instead, decision-makers should act according to the *level* of uncertainty they identify and select the most attractive strategy for handling uncertainty in each case (Courtney, Kirkland and Viguerie, 1997; Thissen and Agusdinata, 2008). Walker *et al*. (2003) extend the evaluation beyond the level, considering, in addition, *location* and *nature* of the uncertainties as relevant dimensions for the selection of a strategy. Similarly, Haberfellner and de Weck (2005) consider the *time* dimension as the differentiating factor to handle uncertainty in design problems, distinguishing between strategies for handling uncertainty during, and after the design process. The time dimension is considered, as well, by Brashers (2001), who differentiates between short- and long-term uncertainties.

In other words, managing uncertainty is to understand who needs information, what kind of information is needed, why and when; and to find ways to obtain it (Danilovic and Sandkull, 2005) or ways to reduce its effects when the information required is not available (Brashers, 2001). Regardless of the type or level of uncertainty, decision-makers have, generally, four strategic alternatives when facing uncertainty in decisions (Thissen and Agusdinata, 2008): (a) ignore, (b) delay, (c) reduce and (d) accept. These strategies may be seen as adaptations to the 4T's of loss control management literature: terminate, treat, transfer or tolerate (Bird and Germain, 1985).

a) Ignore uncertainty – make a decision and wait to see what happens. Base decisions on beliefs regarding the likelihood of future uncertain events (Tversky and Kahneman, 1974). Assume that the future is a candid, truthful examination of past experience (Keynes, 1937).

b) Delay decisions – wait until uncertainty has been reduced over a certain time period. Concurrent engineering (Mistree *et al.*, 1990), set-based design (Singer, Doerry and Buckley, 2009) or "Wait and see" optimization (Diwekar, 2003) are some examples. "Probe and learn" (Lynn, Morone and Paulson, 1996), as a strategy for new product development is also considered within this group, although it could also be considered as a strategy to reduce uncertainty.

c) Reduce uncertainty – by increasing the level of knowledge available. Research, analysis or simulation are cost-effective means for gaining knowledge and therefore reduce uncertainty (Peace Cox, 1974). Improve communication techniques and management (Brashers, 2001). Prototyping, joint venture/partnering are also recognized as strategies to reduce uncertainty in projects and product development (Fox *et al.*, 1998).

d) Accept uncertainty – understand it and act consciously in its presence. Taking a decision under an acceptable level of uncertainty requires a strategy to protect or prepare for the consequences of an arising uncertainty. The protection or preparation can be done passively or actively; where the former considers a unique decision point, and the latter a succession of decisions over time as uncertainty factors arise. In design decisions, these strategies are employed in both, the process, the asset or design, and the operational strategy (Haberfellner and de Weck, 2005). de Neufville (2004) highlights the last two, denominating *control* uncertainty to the reduction, and *protection* to the acceptance of uncertainty. The latter is divided into active and passive protection; where the first consider strengthening the design to avoid surprises, while the second focuses on changeable designs. A comparison of these two strategies in the design of an offshore construction vessel is presented by Rehn *et al*. (2018). Their findings suggest that versatility is of relevance for vessels operating in short-term contracts, spot market, although requires an upfront investment. Retroffitability is, however, of more interest for vessels operating in longer contracts, which have the possibility of converting and adapting before entering into a new contract.

A central goal of uncertainty management is avoiding surprise (McDaniel and Driebe, 2005). The future is unpredictable, or at least difficult to predict in complex environments. Since it is almost impossible to know with full certainty the future, reduce and accept strategies consider taking decisions on the most probable or expected future(s) or based on a variety of potential ones. Techniques like scenario planning (Schoemaker and van der Heijden, 1992) and assumption-based planning (Walker, Haasnoot and Kwakkel, 2013) are used for this purpose. An example of this is Subsea 7, a subsea contractor in the offshore energy industry which considers scenarios for the assignation of capital expenditure in their strategic market positioning (Subsea 7, 2017). Further, the use of scenarios in presented with a practical application on the design of a jack-up installation vessel; see more details in Section 2.3.3.3.

Design decision-making problems will, in most cases, involve uncertainty that is multi-layered, interconnected and temporal. As such, uncertainties from different nature, type and temporal distribution may coexist. Hence, the manipulation of one type of uncertainty may impact (positively or negatively) others (Brashers, 2001). This requires, therefore, a better understanding of causality and interdependency among uncertainties affecting the decision-making process (Pearl and Mackenzie, 2018).

2.2.1. Definitions of uncertainty

In general terms, uncertainty is defined as: "The state of being uncertain; something you cannot be sure about" (Oxford Dictionary Online, 2016), "A situation in which something is not known, or something that is not known or certain" (Cambridge Dictionary Online, 2016) and as "The quality or state of being uncertain; something that is doubtful or unknown: something that is uncertain" (Merriam-webster Dictionary Online, 2016). The quality of state that characterizes uncertainty, makes it susceptible to change; to be influenced by human agents or contextual factors.

Table 2-5 Collection of definitions of uncertainty.

Field	Definition of uncertainty	Source
Economics	*"a situation for which is not possible to specify numerical probabilities"*	(Knight, 1921, p. 20)
	"*there is no scientific basis on which to form any calculable probability whatever. We simply do not know*"	(Keynes, 1937, p. 214)
Management	"*lack of knowledge as to whether an event will have meaningful ramifications; cause and effect are understood, but is unknown if an event will create significant change*"	(Bennett and Lemoine, 2014, p. 313)
Decision-making	"*any departure from the unachievable ideal of complete determinism*"	(Walker *et al.*, 2003, p. 9)
	"Information deficiency", "data deficiency"	(Ayyub, 2015, p. 4)
	"something that is unknown or not perfectly known"	(Skinner, 2009, p. 14)
Design	*"things that are not known, or known only imprecisely"*	(McManus and Hastings, 2005)
	"lack of definition, lack of knowledge and lack of trust in knowledge"	(Wynn, Grebici and Clarkson, 2011, p. 187)
	"potential, unpredictable, unmeasurable and uncontrollable outcome"	(Antunes and Gonzalez, 2015, p. 217)
	"a lack of precise knowledge regarding the inputs to a model or process, or the model or process itself, or about future events that will influence the outcome of a decision"	(Hazelrigg, 1999, p. 343)
Physics	*"limitation of operational possibilities imposed by quantum mechanics"* *(From Heisenberg's uncertainty principle)*	(Busch, Heinonen and Lahti, 2007, p. 155)
Social science	*"Not knowing for sure what will happen"*	(Stalker, 2016, p. 214)
	"the state of an organism that lacks information about whether, where, when, how, or why an event has occurred or will occur"	(Bar-Anan, Wilson and Gilbert, 2009, p. 123)
	"when details of situations are ambiguous, complex, unpredictable, or probabilistic; when information is unavailable or inconsistent; and when people feel insecure in their own state of knowledge or the state of knowledge in general"	(Brashers, 2001, p. 478)
Psychology	*"a state of mind characterized by doubt, or a conscious lack of knowledge about the outcome of an event"*	(Head, 1967, p. 206)

In economic literature, uncertainty is seen as a situation which is not possible to specify quantitative (Knight, 1921) or scientifically (Keynes, 1936, 1937) its probability. Decision-making theorists, similarly to design practitioners (McManus and Hastings, 2005), relate uncertainty to the lack, inaccuracy or deficiency of information (Walker *et al.*, 2003; Ayyub, 2015). On the other hand, psychology literature defines uncertainty as to the state of mind characterized by a conscious lack of knowledge about the outcomes of an event (Head, 1967). The definition from social science and psychology relate to the *subjective* nature of uncertainty, describing it as a "state of mind" (Head, 1967, p. 207) or "state of an organism" (Bar-Anan, Wilson and Gilbert, 2009, p. 123), hence it is based on a personal perception. Supporting this view, Brashers (2001) relates uncertainty to the insecurity of people with regards to their own knowledge. Boschetti (2011) makes the distinction between "how uncertain we are" and "how aware we are of uncertainty" in order to encapsulate the effect of subjectivity. Table 2-5. includes an overview of definitions of uncertainty in different research fields.

Today, although somehow still overlapping, the literature reflects a differentiation between risk, as cause-effect relation based on a probability, and uncertainty, as the lack of knowledge (Saunders Pacheco do Vale and Monteiro de Carvalho, 2014). See Section 2.2.3 for more details.

Uncertainty contributes to the overall complexity of problem-solving both, by means of intransparency and politely (Funke, 1991). Intransparency relates to the lack or poor availability of information while politely relates to the multiplicity of goal, which may result from a poor definition of goals. Uncertainty is here seen as a superset of a variety of terms, all of them relating to the lack of certainty about something or someone. Thunnissen (2003) also recognises the multiplicity of concepts that uncertainty has come to encompass overtime. Yet, we recognize, that the different words give a special connotation to the different types of uncertainty. However, by working at a higher level of definition we avoid the discussions at a lower definition level such as those on the differences between ambiguity and uncertainty; briefly discussed in the next paragraph.

Ambiguity, according to Ellsberg (1961), relates to the nature of information regarding the likelihood of events. This definition equates Knights (1921) definition of uncertainty. However, Pirner (2015) distinguishes between uncertainties with known probabilities, *ambiguity*, of those with unknown or unclear probabilities, *incertitude*. His definition of ambiguity goes, by definition, against what Ellsberg defines as ambiguity or Knight's uncertainty. Contrary, Carbone *et al*. (2017, p. 87) define ambiguity as "a situation in which probabilities either do not exist or are not known". See a more detailed discussion on the differences in risk and uncertainty in Section 2.2.3.

Based on the literature reviewed and the definitions of the multiple connotations of uncertainty used in the different applications, industries and research perspectives, we may group the different connotations of uncertainty in three groups: (i) Relating to the definition, (ii) relating to the understanding, and (iii) relating to change. The definitions proposed by the Oxford Dictionary (2016) of the different connotations are included below.

Relating to the *definition* of an item, we find (i) indefinite: “Lasting for an unknown or unstated length of time; not clearly expressed or defined; vague”, (ii) unknown: “Not known or familiar”, (iii) indeterminate: “Not exactly known, established, or defined”, (iv) undefined: “Not clear or defined”, and (v) indistinct: “Not clear or sharply defined”. Similarly, relating to the *understanding* of an item, we find (vi) Ambiguous: “Open to more than one interpretation; not having one obvious meaning; not clear or decided”, (vii) unclear: “Not easy to see, hear, or understand; not obvious or definite; ambiguous”, (viii) vague: “Of uncertain, indefinite, or unclear character or meaning; thinking or communicating in an unfocused or imprecise way”, (ix) insecure: “Not firm or fixed; liable to give away or break”, and (x) doubtful: “Feeling uncertainty about something; not known with certainty”. Finally, relating to *change* of an item, we find (xi) dynamic: “A process or system characterized by constant change, activity, or progress”, (xii) volatile: “Liable to change rapidly and unpredictably, especially for the worse”, (xiii) random: “Made, done, or happening without method or conscious decision; governed by or involving equal chances for each item”, (xiv) unpredictable: “Not able to predict; changeable” and (xv) unstable: “Likely to change or fail; not firmly established”.

2.2.2. Uncertainty as to the error of prediction

The error, or uncertainty, of a prediction, is described by three factors: (a) bias, (b) variance and (c) noise. Hence, the total error will result in the addition of these three terms as presented in Equation 1, or mathematically in Equation 2. The two factors are not independent, hence, reducing bias tends to increase variance, and vice-versa (Brighton and Gigerenzer, 2015).

$$\boldsymbol{Total\ error = bias^2 + variance\ + irreducible\ noise} \qquad \text{Equation 1}$$

$$\boldsymbol{Err(x) = \left(E[\hat{f}(x)] - f(x)\right)^2 + E\left[(\hat{f}(x) - E[\hat{f}(x)])^2\right] + \sigma_e^2} \qquad \text{Equation 2}$$

The bias component of a model represents its inability to represent the predictive regularities governing the observations. For a data sample, bias is the difference between the *mean* response of the models fitting the individual data points and the *true* model. The variance component of a model represents the sensitivity of the model to different observations of the same problem. For a data sample, the variance is a measure of the degree to which the models fitting the individual data points vary about their mean. Some researchers combine variance and noise in a unique component defined as noise. This noise may be resulting from variability across occasions (hence, context-dependent) or across individuals (hence, agent dependent) (Kahneman *et al.*, 2016).

The variability component of errors in predicting models reminds of the limited applicability of predictive models in uncertain environments. A certainty (prediction based on a reliable model) may become uncertainty if a factor outside the model’s control varies in the environment changes. Taleb (2010) suggests that the reason for this limited applicability of predictive models is its inductive nature. The same limitation applies to the expert’s judgment (King, 2019). In some circumstances, certainties are so because no one could demonstrate the opposite. After all, the Earth was *certainly* flat until Aristotle could demonstrate its spherical shape around 330 BC. So, to which extent can we trust certainty?

The validity of predicting models is defined by its *statistical significance*. The goodness-of-fit of a prediction model for a given sample doesn't suffice. The reliability of a model should persist across a variety of assumptions and data sets (King, 2019). Does the model fit historical data independently of the time frame selected? Taleb (2010) names *Mediocristan* those factors that can be predicted based on statistics, while *Extremistan* cannot be predicted from historical data. It is the responsibility of the decision-maker to understand what type of factor he or she predicts and respectively the statistical significance of the model. This should define the trustfulness on the estimates, and influence in the final decision. For more discussions on the reliability and validity of the results, please see the discussion in Section 5.2.

2.2.3. On the differences between uncertainty and risk

In 1921, Frank H. Knight (1885-1972) proposed a distinction between "measurable uncertainty" or "risk" and "unmeasurable uncertainty"; where the former represents the probability of an outcome when it is possible to calculate (or is knowable), and the latter represent it when the outcome is not possible to determine (or is unknowable) (Knight, 1921). A similar interpretation was proposed by Keynes, who states "…human decisions affecting the future, whether personal or political or economic, cannot depend on strict mathematical expectations since the bases for making such calculation [probabilities] does not exist" (Keynes, 1936, p. 92). Despite this early distinction, the difference between risk and uncertainty hasn't been fully integrated among researchers and practitioners (Müllner, 2016).

Knight's proposal raised some skepticism among practitioners in the risk management field (Ellsberg, 1961), since its unmeasurable uncertainty wouldn't be possible in a rational world following the reasoning of authors like Frank P. Ramsey (1903 – 1930) or Leonard J. Savage (1917 -1971), "for a rational man – all uncertainties can be reduced to risks" (Ellsberg, 1961, p. 645). Although in many cases is possible to assign probabilities to the outcome of decisions, not all might prove to be fruitful (Ellsberg, 1961; Taleb, 2010). In such circumstances, probabilities are defined based on the information available to each decision-maker and its interpretation of it (Ellsberg, 1961). Hence, each decision-maker will have its own prediction of probability (Miller, 1977). This implies that, although it is possible to assign probabilities to almost every decision-making problem, in many cases, the reliability of such probabilities will mislead the decision, as it will not lead to maximization of outcomes. Thus, Taleb (2010, p. 128) suggests that Knight's computable risks (measurable uncertainty) are not found in real-life situations, and they are only the result of laboratory contraptions.

Building on Knight's works, Perminova (2011) suggest that while risk is calculable and can be eliminated, uncertainty is not calculable and cannot be completely eliminated. "Risk is known, calculable and it can be foreseen, hence eliminated or avoided. Uncertainty is not subject to calculations, it cannot be eliminated completely, but it can be acted upon, for example, to gain benefits" (Perminova, 2011, p. 45). Some authors, like Neth and Gigerenzer (2015) go beyond the probabilistic discussion, and suggest that uncertain decisions are characterized by unknown decision alternatives, probabilities and consequences or a combination of them, while risk management assumes them as known. From his point of view, Sidorenko (2019) suggests that risk analysis can be categorised into two groups, (i) techniques to better understand the nature of risk, (ii) techniques to better understand how uncertainty affects decisions and objectives. Hence, his distinction between uncertainty handling and risk management is the fact that in the latter, risks are known. In their work, Saunders and Monteiro (2014) identify several interpretations of risk and uncertainty, from authors which used them as synonyms (De Maio, Verganti and Corso, 1994), to others who treat them as different aspects (Zwikael and Globerson, 2006). However, for projects related to dynamic environments, Saunders and Monteiro (2014) recommend to go beyond risk management methodologies and explore alternative strategies.

The International Organization for Standardization (ISO) defines risk to be the "effect of uncertainty on objectives", where the effect is "a deviation from the expected. It can be positive, negative or both, and can address, create or result in opportunities and threats" (ISO, 2018). A similar interpretation is proposed by Hazelrigg (1999, p. 343), who defines risk as "the result of uncertainty on the outcome of a decision". This definition contrasts with traditional theories which built their differentiation between risk and uncertainty on the fact that the former relates only to negative effects, while the latter including also upside opportunities (Hillson, 2002). For example, market uncertainty with regards to the availability of yards to build a specialized vessel can give rise to higher price offers than otherwise would be the case. This will have a positive effect on the yard but not for the vessel investor. This definition proposes a different perspective than the one suggested by Mun (2006), who argues that risk is the result of a decision taken is in spite of uncertainty; although uncertainty alone does not imply risk. Yet, the fact of not making a decision and delay or ignore it is in itself a decision, which may involve risk. If a company doesn't make an investment but a competitor does, this may put in risk that company's business. The same interpretation of uncertainty is proposed by Kahneman (2011, p. 141) who takes from the words of Paul Slovik (1938-) that "Human beings have invented the concept of risk to help them understand and cope with the dangers and uncertainties of life".

Luce and Raiffa (1957) propose three decision-making situations: certain, risky and uncertain. The former results on known outcomes, while the latter two are characterized by unknown outcomes. Risk situations relate outcomes to a probability of occurrence, while uncertain situations don't. A similar differentiation is found in the work of Taghavifard *et al*. (2009), who name certain situations as deterministic. Figure 2-12 represents graphically this distinction. With determinism on the left side and uncertainty on the right side. All the situations between those two extremes represent combinations of determinism and pure uncertainty and may be managed by risk management techniques.

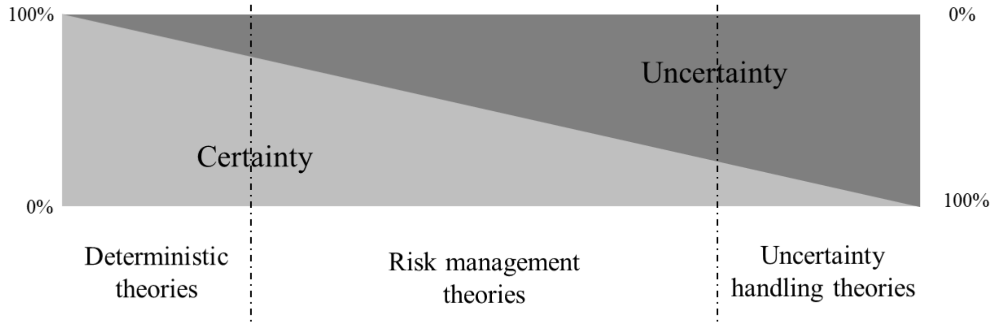

Figure 2-12 Distribution of methodologies for different ranges of uncertainty.

Both risk and uncertainty are referred to as subjective matters. Thus each decision-maker will have its own interpretation of risk and uncertainty (Riabacke, 2006; Taghavifard, Damghani and Moghaddam, 2009). Samset (1998) suggests however that uncertainty is the objective reflection of the unknown, while risk and opportunity are the subjective perceptions of uncertainty by different human-beings. Relating to Figure 2-12, this means that in some cases, determinism and uncertainty will be considered only as of the extremes of the rectangle, 100% certainty, and 100% uncertainty respectively, and risk in between, from 99% certainty to 1%. In other cases, this distinction is interpreted differently, and risk situations are only those between, for example, 25 and 75% certainty. The stage between uncertainty and risk is referred to by Kleindorfer (2008) as ambiguity. The final distinction between risk and uncertainty is made by the decision-maker. In the first case, we may say decision-makers are risk-takers, while in an uncertain situation they may be related to gamblers (Riabacke, 2006).

To differentiate between risk and uncertainty in decision-making situations, many authors have utilized exaltations of uncertainty, indicating that a specific decision is made under circumstances where it is not possible to define probabilities. Some examples are: *pure* uncertainty (Taghavifard, Damghani and Moghaddam, 2009), *high* uncertainty (Johansen *et al.*, 2014), *deep* uncertainty (Walker, Lempert and Kwakkel, 2013; Kwakkel, Haasnoot and Walker, 2016), significant uncertainty (Vrijdag, Stapersma and Grunditz, 2012; Almandoz and Tilcsik, 2016), *true* uncertainty (Müllner, 2016), *considerable* uncertainty (Kochan and Rubinstein, 2000) or *severe* uncertainty (Comes *et al.*, 2011; Bradley, 2012).

One additional perspective to explore the differences between risk and uncertainty relates to the type of tools used in each situation. Neth and Gigerenzer (2015) suggest that certain situations where all necessary information is available shall be taken based on logic. However, in situations where the decision-maker knows the consequences of its decisions and their associated probabilities, decisions shall rely on probability and statistics. Finally, in situations where neither alternatives nor probabilities are known, decision-making shall rely on heuristics. Overall, in decision-making situations under uncertainty where there exist one or a few unknown factors, it is very important to understand how uncertainty affects the decisions and its outcomes (Sidorenko, 2019).

In this research, uncertainty is considered as any situation outside pure certainty, independently of the degree of uncertainty.

2.2.4. Quantification of uncertainty

The importance of understanding and quantifying the level of uncertainty in decisions has been of interest for the management research literature since the late 60's. Despite this, little work has been done in order to identify and validate the causal sources of such uncertainty (Fleming, 2001). Downey and Slocum (1975) argue that, in order to manage in a useful way uncertainty in decision-making processes, it is required to operationalize it; construct instruments to identify it and measure it; starting by understanding how individuals perceive it. Fleming (2001) suggests that the understanding of uncertainty in decision-making depends on the understanding that the decision-maker has of the decision process. Hence, a quantitative perspective of uncertainty should generate a better foundation to improve decision-making, and also provide a foundation to better understand trade-offs and informed decisions (Hopper and Spetzler, 2016). Similarly, Pawlina and Kort (2003) suggest that volatile environments require appropriated identification of the sources of uncertainty in order to perform effective business activities. Yet, this work contrast with some authors who consider that uncertainty, by definition, is unquantifiable (Perminova, 2011).

Uncertainty is not static, it will increase or decrease over time, as more information is gained or as new external factors are operationalized (McManus and Hastings, 2005). Antures and Gonzalez (2015) suggest that in project developments, uncertainty decreases throughout the lifetime of the project as new information is available and the estimates become more robust. Based on this assumption, McConnell (2009) and Antures and Gonzalez (2015) propose a cone of uncertainty, as shown in Figure 2-13. In the cone of uncertainty proposed by Antures and Gonzalez, it can be perceived that during the feasibility phase uncertainty is reduced to half, and further reduced through the design and construction phase. At completion, the uncertainty relating to the variability of estimates is fully eliminated. Although the authors do not demonstrate how uncertainty, or variability in the estimations, in this case, is calculated, it shows the importance of understanding the different degrees or levels of uncertainty throughout the project.

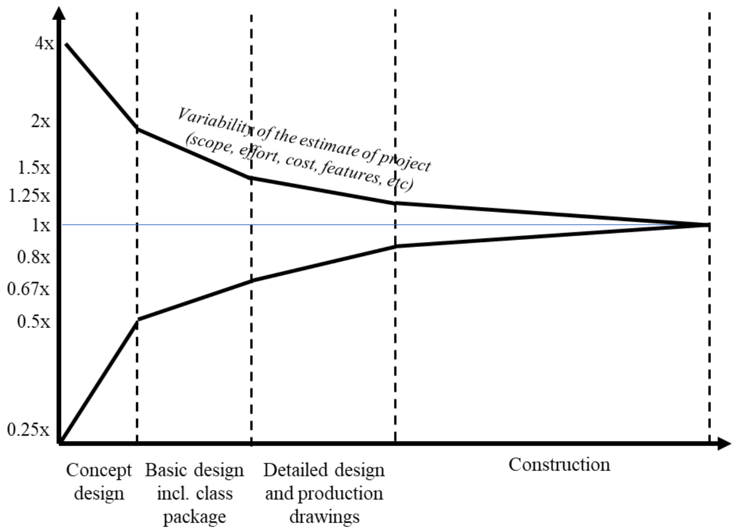

Figure 2-13 Cone of uncertainty adapted to a ship design process. Reference values are taken from Antunes and Gonzalez (2015, p. 219).

The definition of a measure of uncertainty allows for the valuation of information (Pirner, 2015). If we can measure uncertainty, then we will be able to quantify how much uncertainty is reduced given a specific quantity of information. Pirner (2015) proposes a measure to identify the value of new information towards the reduction of uncertainty. The worth of information (WIN) represents the relative change in complexity to the change in indefiniteness (aka uncertainty), as presented in Equation 3.

$$WIN = \frac{\Delta Complexity}{\Delta \log\,(indefinitiness)} \qquad \text{Equation 3}$$

From a different avenue, one of the pioneer jobs regarding uncertainty quantification was the questionnaire-based evaluation carried out by Lawrence and Lorsch (1967). The authors evaluate three uncertainty elements: *lack of clarity*, general uncertainty of *causal relationships* and *timespan* of feedback; generating the overall uncertainty of the firm as the summary of those three. Their study, focused on 10 U.S. industrial firms, was later expanded by Tose, Aldag, and Storey (1973) to 22 firms representing 12 industries. The latter publication found some discrepancies with Lawrence and Lorsch's measurements, based on the results obtained from their analysis, and further question the validity of the methodology. Downey and Slocum (1975) and Downey, Hellrieger, and Slocum (1975), however, question the interpretation of the results from Tosi *et al*., basing it on misinterpretations and lack of clarity in results. Similarly, Duncan (1972) proposes a new measure of perceived uncertainty in organizations based on two dimensions, *complexity*, and *dynamism*. The work of these researchers during the late '60s and '70s represents the first steps on intent for better understanding uncertainty by identifying those factors contributing to increasing the perceived uncertainty by decision-makers. Still, Milliken (1987) argues about the inconsistency and difficulty to interpret results from these previous research studies; suggesting that there is still little theoretical significance for the construct of uncertainty, and especially environmental uncertainty.

With regards to uncertainty, there exist two postulates among the literature reviewed. A group of researchers advocates measuring uncertainty as a perceptual phenomenon (*perceptual uncertainty*), while others consider it as objective (*actual uncertainty*), warning that the consequences of evaluating uncertainty as a perceptual matter would be the psychoanalysis of actors rather than uncertainty (Milliken, 1987). This research work distinguishes between actual and perceived uncertainty. The actual uncertainty in a decision-making process is a measure that is related to the lack of complete information. Contrary, perceived uncertainty represents the information that a specific stakeholder believes he or she is lacking. The terms actual and perceived have been taken from risk management literature, a recent example being Charlton *et al*. (2014).

Some studies (Tosi, Aldag and Storey, 1973; Downey and Slocum, 1975; Downey, Hellriegel and Slocum, 1977) has pursued to measure both, actual and perceived uncertainty. In those studies, uncertainty was operationalized by measures of environmental volatility. As described in the previous paragraph, the validity and significance of the findings in these studies have been questioned. One of the challenges in the interpretation of the results is that the two most commonly used scales, proposed by Lawrence and Lorsch (1967) and Duncan (1972) respectively, measure different concepts (Downey and Slocum, 1975; Downey, Hellriegel and Slocum, 1977). The operationalization proposed by Lawrence and Lorch (1967) measures the ambiguity of requirements, feedback delay, and complexity. On the other hand, Duncan (1972) considers a lack of information, to the lack of predictability of future events and lack of knowledge regarding the consequences of decisions. The challenges and difficulties found during the late ’60s and ’70s on the measurement of uncertainty and the discrepancies regarding the perception of uncertainty have, most likely, discourage further research, as represents the little research carried out in this topic afterwards. Miller (1993) points out that a major challenge for empirical research on perceived uncertainty is the lack of a well-established measurement instrument.

More recently, the quantification of uncertainty has gained interest within fields such as medical sciences (Tamburini *et al.*, 2000; Harkness, Arthur and McKelvie, 2013; Cleanthous *et al.*, 2016), management (Priem, Love and Shaffer, 2002; Ashill and Jobber, 2010; Regan, 2012; Folami and Powers, 2014), energy markets (EIA, 2009) and science (Retzbach, Otto and Maier, 2016). Most of the research work reviewed in this thesis, on the quantification of uncertainty, has focused on environmental uncertainties (Priem, Love and Shaffer, 2002). Höllermann and Evers (2017) find contraposition between practitioners and scientists with regards to types of uncertainties and strategies to cope with them. They find that scientists focus on the quantification and reduction of uncertainty, with special emphasis on environmental uncertainty. On the other hand, practitioners apply risk-based decision approaches to cope with process uncertainties. It is the goal of this research to build a bridge connecting these two different perceptions of uncertainty and strengthening the future handling of uncertainty.

A recent example of quantification of actual uncertainty is Salaken *et al*. (2017). The authors present an uncertainty score which reflects the confidence of an output. The uncertainty score is a ratio of the derived solution space (S_D) to the global solution space (S_G). In their definition, the global solution space (S_G) represents the space which boundaries are defined by the rule base, while the determined solution space (S_D) is the one defined based on a given input. As such, the uncertainty score (U) is defined as the percentage of the determined centroid shoulder to the global solution space, as presented in Equation 4. Hence, the higher the uncertainty score (U), the lower the confidence of the decision support tool on its output recommendation. The measure differs from the traditional *error* (potential deviation from the output) as it reflects the uncertainty of the output based on the uncertainty present in the input, rather than giving a reference of how good the estimation of output is.

$$U = \frac{S_D}{S_G} \times 100\% = \frac{\left|S_{D_{max}} - S_{D_{min}}\right|}{\left|S_{G_{max}} - S_{G_{min}}\right|} \times 100\% \qquad \text{Equation 4}$$

Another perspective is explored by Jurado, Ludvigson, and Ng (2015) who describe actual uncertainty (from an economic perspective) as presented in Equation 5. The uncertainty (U) regarding the variable (y_{jt}) in a future time (h) is expressed as the conditional volatility of the measure. Therefore, if the expectation (E) based on the information available at the time (I_t) of the squared error in forecasting increases, so the uncertainty.

$$U_{jt}^{y}(h) \equiv \sqrt{E\left(\left(y_{jt+h} - E\left(y_{jt+h}\middle|I_t\right)\right)^2 \middle| I_t\right)} \qquad \text{Equation 5}$$

A similar interpretation of uncertainty is assumed by the *Energy Information Administration*, the *U.S. Federal Reserve Bank* or the *Bank of England*, to assess market uncertainty (EIA, 2009). The quantification of uncertainty by these entities is based on the drafting of confidence intervals around expected future prices. Such confidence intervals represent the standard deviation of expected returns and are calculated based on statistical data. Jurado, Lugvigdon, and Ng (2015) present the macroeconomic uncertainty or overall uncertainty as presented in Equation 6, being w_j the aggregation weights. The authors look as well into the influence of agent behaviour, expanding Equation 5 and Equation 6 to an agent-based analysis. For simplicity, the latter extension is not included here.

$$U_t^{y}(h) \equiv \operatorname*{plim}_{N_y \to \infty} \sum_{j=1}^{N_y} w_j U_{jt}^{y}(h) \equiv E_w\left[U_{jt}^{y}(h)\right] \qquad \text{Equation 6}$$

There exist alternative indices measuring uncertainty on a macro-economical perspective, such as the world uncertainty index (WUI). The WIU consist of quarterly updated indices measuring the economic uncertainty of 143 countries, with data available since 1996. The index is calculated based on the frequency of use of the "uncertainty" word and its variants in the quarterly *Economist Intelligence Unit* reports. By exploring the evolution of the WUI index among different countries (see Figure 2-14), it is observed a clear difference between the WUI of advanced economies and those of other countries. Countries of advanced economies present, on average, a lower uncertainty index. Further, the WUI index is positively associated with economic policy uncertainty and stock market volatility, and negatively with GDP growth (Ahir, Bloom and Furceri, 2018).

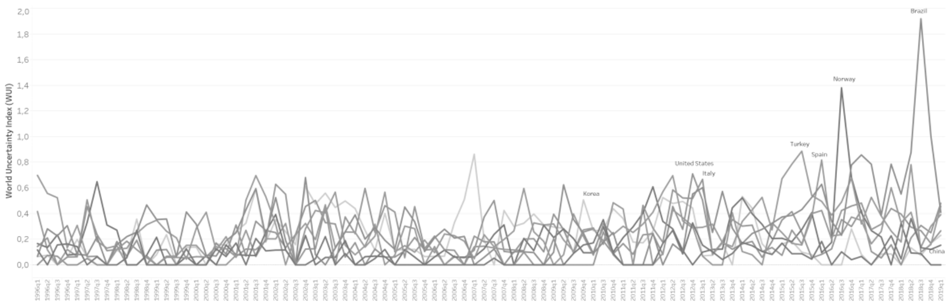

Figure 2-14 Development of world uncertainty index (WUI) for selected countries. Data from (Ahir, Bloom and Furceri, 2019).

A similar volatility quantification index is the global economic policy uncertainty (GEPU). The GEPU index is being calculated, on a monthly basis, as the GDP-weighted average of national economic policy uncertainty (EPU) indices for 20 countries. The EPU index is calculated based on the number of articles published in national newspapers relating to economy (E), policy (P) and uncertainty (U). Looking at the evolution of the index over time (see Figure 2-15), it is perceived that the current levels of global economic policy uncertainty (GEPU) are substantially higher compared to recent history, especially before the financial crises in 2008. Since 2008, economic policy uncertainty has averaged about twice the level of the previous 23 years (Baker, Bloom and Davis, 2016).

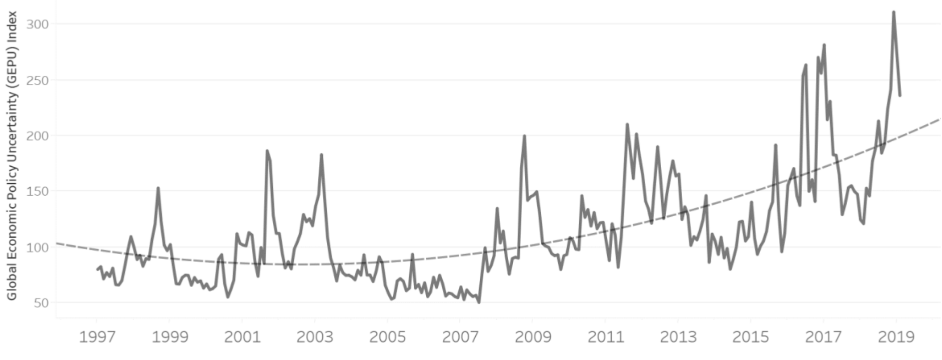

Figure 2-15 Global economic policy uncertainty (GEPU) index, current-price GDP measures. Data from (Baker, Bloom and Davis, 2019).

2.2.5. Actual and perceived uncertainty

In the previous section of this thesis, the concepts of *actual* and *perceived* uncertainty were introduced, together with a definition commenting on the differences between the two terms. This difference surges from the fact that uncertainty can be perceived and interpreted differently (Wainer, 2009). The actual uncertainty in a decision-making process is a measure that is related to the lack of complete knowledge while perceived uncertainty represents the knowledge that a specific stakeholder believes he or she is lacking.

Millike (1987), one of the few pursuing this topic together with Miller, recognizes the need for further research and elaborates in some reflections. Millike argues that a perfect balance between perceptual and actual uncertainty is not realistic since perceptual uncertainty will be influenced by the context, individual attributes, and limitations of cognitive reasoning. One reason for this mismatch is found on metacognitive ignorance. Kruger and Dunning (1999) suggest that unskilled people are more susceptible to underestimate their ignorance than a skilled one. His argument builds on the fact that the knowledge required to make a judgment is the same than the one required to assess the quality of such knowledge. At low levels of knowledge or experience, the delta of confidence for each delta of knowledge is high. Hence, subjects gain relatively quickly a high level of confidence. However, shortly after, they realize that there is a lot of information that is still lacking, and therefore they lose that confidence as quickly as they have gained. Confidence is gained again but at a slower rate thereafter.

The differentiation between actual and perceived is well documented in the risk management literature (Danielsson, Shin and Zigrand, 2012; Charlton et al., 2014). In Figure 2-16, it is presented a comparison between actual risk and perceived risk in financial investments. Perceived risk is here at its lowest value when the actual risk is at the highest, as result of the human response to external factors, in what is named emotional finance (Bullman and Fairchild, 2012). Taken as a reference to the recent oil crises in 2014, and the bubble line relating to the oil price, we can interpret Figure 2-17 as follows. Initially, with medium-level oil prices (~80 USD/bbl), the risk is perceived high since the return from the investment of a new field is lower. As the oil price increases, investors will become more confident, hence perceived risk will decrease. This perceived risk will increase again subsequently with a reduction of oil prices. Contrary, the actual risk will present a different pattern, as it will increase together with the oil price, since there will be more investors willing to enter the market, and their investments will be based only on high oil prices. This behaviour has been described by Garcia, Brandt, and Brett (2016b) relating to the offshore support vessel market.

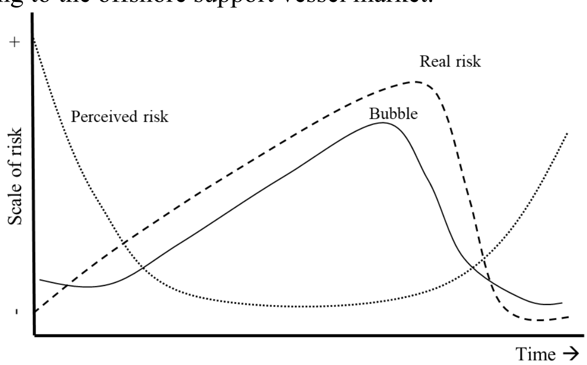

Figure 2-16 Graphical representation of actual and perceived risk (based on (Bullman and Fairchild, 2012)).

An example of the influence of culture and agent in the perception of uncertainty is the uncertainty avoidance index (UAI) proposed by Hofstede (2001). The UAI represents the comfort of a person in unstructured situations, relying on the fact that uncertainty generates anxiety. Hofstede (2001, p. 146) suggest, however, that "Human society has developed ways to cope with the inherent uncertainty of living on the brink of an uncertain future. These ways belong to the domains of technology, law, and religion". Technology, for example, has focused on describing and imitating the natural, as well documented in (Simon, 1996), and religions, may be seen as an escape to give meaning to the unknown. It is the integration of these domains what characterizes the different cultures regarding their uncertainty avoidance index. Greece, Portugal, and Guatemala have the highest UAI, as opposed to Denmark, Jamaica and Singapore with the lowest (Hofstede, 2001). Hence, the former cultures will rely more deeply on rules, laws and ritualistic strategies than the latter cultures. Merkin (2006) argues that in many cultures, celebrations and ceremonies are seen as a way of controlling the future. In ship design and building, we could see the traditional steel-cut ceremony, keel laying or launch as an indirect way for the stakeholders to feel that the project is still under control. These are not more than intermediate control points which, at an earlier stage give partial information regarding the final product, the vessel and its delivery time. Finally, uncertainty avoidance has been found also to be influenced by personal factors such as occupation and gender (Hofstede, 2001; Merkin, 2006).

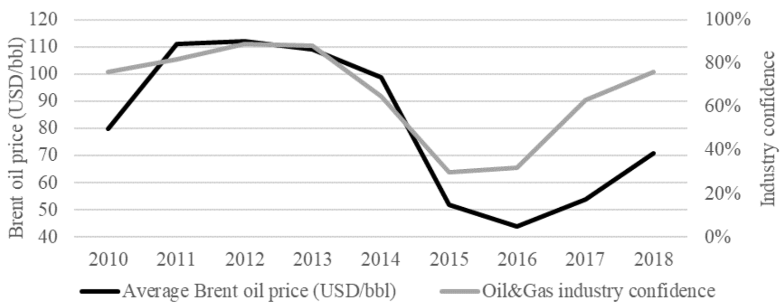

Figure 2-17 Average Brent oil price and industry confidence (2010-2018). Data from (DNV.GL, 2019).

The distinction between actual and perceived uncertainty recalls to the popular question of the falling tree: "When a tree falls in a lonely forest, and no animal is nearby to hear it, does it make a sound? Why?" (Mann and Twiss, 1910, p. 235). This ontological question has been discussed broadly by thinkers and practitioners of metaphysics since 1710 when George Berkeley brought it in a slightly different version. From a scientific point of view, (S.A.H., 1884, p. 218) concludes "sound is vibration, transmitted to our senses through the mechanism of the ear, and recognized as sound only at our nerve centres. The falling of the tree or any other disturbance will produce vibration of the air. If there be no ears to hear, there will be no sound." Similar reasoning could be done for uncertainty. Data, as vibration does in tree analogy, may be available or exists, but it is the awareness of it, its interpretation and use which generates the information required to reduce uncertainty.

2.3. Strategies for handling/managing uncertainty

Uncertainty is like a two-sided coin (Johansen *et al.*, 2014), resulting potentially on threats or opportunities. As designers or decision-makers, we in the ship design domain should pursue to reduce the consequences of threats and exploit opportunities arising from uncertainty (Hillson, 2002). This is what characterises successful businesses (Taleb, 2010). Hence, uncertainty handling should not focus exclusively on uncertainty reduction, as it has been the case (Hillson, 2002), if not on managing the effects of uncertainty (Brashers, 2001). This requires to go beyond the traditional methods for risk management and adopt, together with techniques focused on planning, strategies directed to flexibility and learning (Saunders Pacheco do Vale and Monteiro de Carvalho, 2014). The selection of a strategy to handle uncertainty should depend on the degree of uncertainty present in the decision-making (Tversky and Kahneman, 1992; Broniatowski, 2017b), hence the importance of coupling the insights from Section 2.2.4 on the quantification of uncertainty and those described in the following paragraphs. Some authors suggest to treat separately endogenous and exogenous uncertainties and later integrate them together in an uncertainty handling model (de Weck, Eckert and Clarkson, 2007). Taleb (2010) suggests investing in preparedness in contrast to overinvesting in *unfeasible* prediction. His argument builds on Pasteur's (1822-1895) cite "in the fields of observation, chance favours only the prepared mind". Pearce (1912) studies more in detail the consequences and premises of a *prepared mind*. A prepared mind builds on observation and can extract opportunities from unforeseen events that a not-prepared mind wouldn't.

The semantic embedding of a problem formulation can have major effects on the uncertainty perceived (Funke, 1991). Vague statements induce uncertainty in decision-makers (Pirner, 2015). A vague statement like a *fast* vessel does not define the speed of the vessel. While the shipowner considers fast a vessel sailing at speeds over 25 knots, the designer may assume fast a vessel sailing at speeds over 18 knots or 16 knots and the like. Cross (2018b) suggest that the design ability of expert designers allows them to handle situations of uncertainty, inadequate information and unclear goals by nature. Building on the recognition-primed decision (RPD) model proposed by Klein (1999), Cross (2018b) suggests that designers rely on the recognition and association of ill-defined problems as standard problems to propose known courses of action. In design situations where the designer is lacking data from the customer, he or she may associate to the latest "similar" project and proceed. Such associations can have benefits, but also negative consequences to the design process and the final vessel design. This is a typical situation in current ship design projects.

In general, we can differentiate between hard and soft methods for handling uncertainty (Pirner, 2015). Pirner contrasts, from a scientific perspective, hard methods such as empiricism, decision theory and fuzzy logic, with soft methods such as metaphors or scenarios. On an engineering level, researchers have developed *qualitative*, *semi-quantitative*, and *quantitative* methods since the 50's looking for a way to account for uncertainty (Rader, Ross and Rhodes, 2010). This reflects the same principles than descriptive, prescriptive and normative decision theories respectively. Qualitative methods involve the evaluation of the likelihood and the consequence of decisions. These methods also include futures techniques which seek to forecast likely future events or capture all possible futures. Semi-quantitative methods base their evaluation on technological maturity, experience and the use of margins. Finally, quantitative methods, principally adapted from economics, seek to generate statistical functions (probability density functions) that correspond to a distribution of outcomes. These methods yield powerful insights, but they are highly sensitive to assumed probabilities and they are unlikely to account for all possible futures. Many of these latter methods build on the premise that some uncertainties (those that can be described by probabilistic methods) can be translated into manageable risks, and take advantage of proven tools and theories from risk management literature (Müllner, 2016).

Overall, as described by Thissen and Agusdinata (2008), decision-makers have four alternatives to handle or manage uncertainty: ignore it, delay the decision, reduce it or accept it. Walker, Haasnoot and Kwakkel (2013) differentiate the latter in four types: resistance, resilience, static robustness and dynamic robustness. Hillson (2002) describes eight strategies for uncertainty handling, four focused on uncertainties leading to threats: avoid, transfer, mitigate and accept (traditionally used in risk management) and four for opportunities: exploit, share, enhance and ignore. The selection of a strategy to handle uncertainty is not limited to the use of one unique strategy. Rather, decision-makers should search for an equilibrium combining different strategies, since some of them are more appropriate for some types or levels of uncertainty than others. Hence, a previous assessment of the various uncertainties is relevant to select the uncertainty handling strategy (Miller, 1993). When selecting an uncertainty handling strategy, the question is not as much which strategy is the best, but which is the better for a certain problem under certain conditions. Further, the applicability and/or usefulness of the different perspectives can depend on the existence of prior experience and the amount of knowledge available (Fischer, Greiff and Funke, 2012).

Time is also an essential factor to take into consideration when selecting a methodology to handle uncertainty. Matheson & Matheson (2016) suggest, for example, that when dealing with operational decisions characterised by quick feedback, it is more attractive to ignore uncertainties, since uncertainties will be learned faster by acting and observing. This, however, doesn’t apply to strategic decisions, where the time required for feedback may involve a large commitment of resources. Thus, for strategic decisions, it is recommended to account for uncertainty to select the decision alternative with the highest risk-return relationship (Matheson and Matheson, 2016).

Understanding uncertainty, its source, type and level are the bases to select the best strategy to handle it (Abrahamsson, 2002; Liwång, 2015). A brief description of the principal strategies and methodologies for uncertainty handling reviewed in this research work are described hereafter in this section, following the categorization proposed in Figure 2-18.

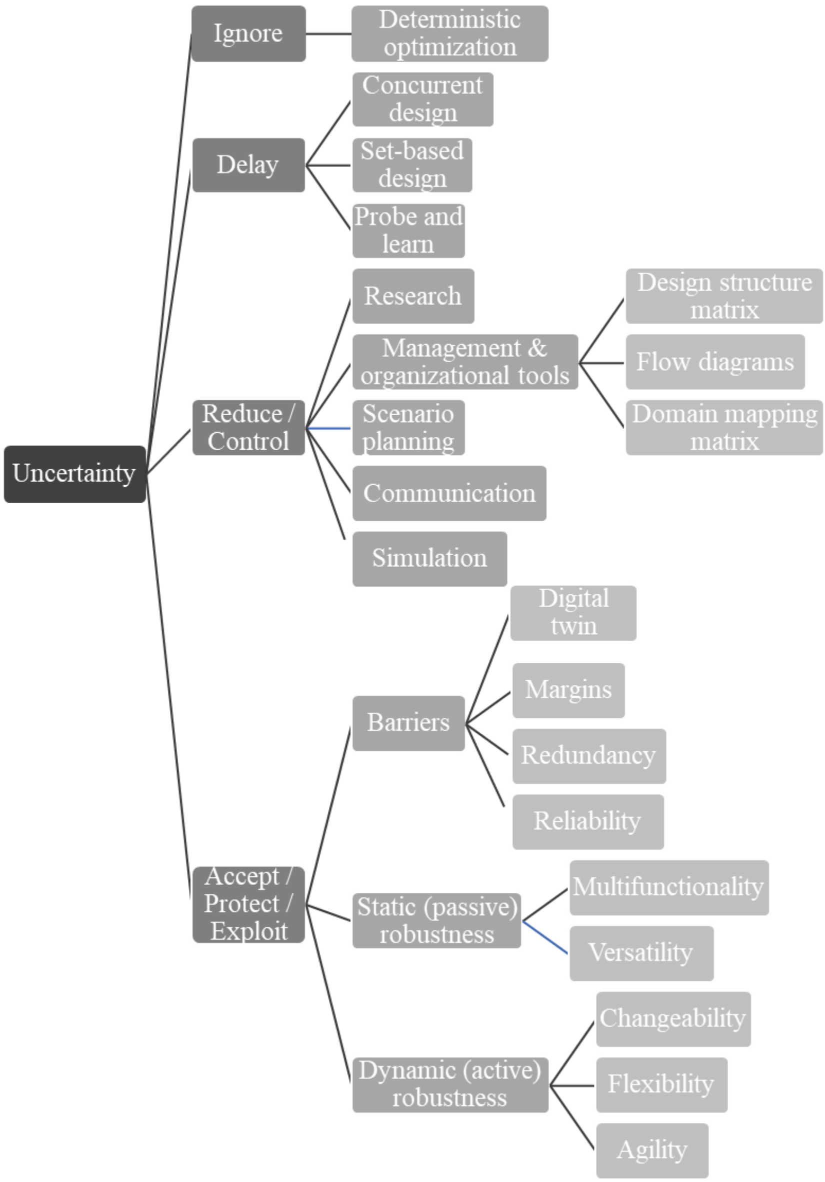

Figure 2-18 Overview of categorizations of uncertainty handling strategies.

2.3.1. Ignore

The ignorance of uncertainty could be the result of both, a conscious decision but it could also be unconsciously. The former is in many cases the result of the use of heuristics as a way of reducing the complexity of decisions taken under uncertainty (Funke, 1991). In many cases, decision-makers assume that factors such as market rates are static, while they aren't. Differently is when a specific factor is not taken under consideration due to the lack of awareness or misunderstanding of it. A recent example is the construction of the factory stern trawler America's Finest. This vessel, after being built, has been considered not eligible as Jones Act compliant and therefore U.S. built, due to excess of foreign steel used in its construction. Even though the vessel was built at an American shipyard, an error interpreting the regulation has limited the use of the vessel for its intended use (Washburn, 2017). Fagerholt et al. (2010) suggest that the complexity and large scale planning required in some decision-making problems lead to the omission of uncertainty by part of the decision-makers. The conscious omission of uncertainty is argued by Haugen and Vinnem (2015) as a problem in the offshore oil & gas (OO&G) industry.

Brunsson (1980) suggests the ignorance of uncertainty as a means to facilitate product-development projects, in contrast with the analysis of it. The recognition of uncertainty may delay decisions in those situations where decision-makers are risk-averse. Human nature inclines decision-makers to ignore indefiniteness (aka uncertainty), to underestimate it or to hide it behind small probabilities or poor explanations (Pirner, 2015). Adaptive heuristics is another research field relying on partial information for decision-making, achieving, in some cases, better results than complete information (Gigerenzer and Gaissmaier, 2011).

2.3.1.1. Deterministic optimization – as a way to influence ignorance

Traditionally, uncertainty has been ignored in conceptual ship design processes, focusing on a deterministic optimization with regulatory constraints taking care of potential technical risks primarily. Very seldom are these technical features contrasted and handled in a broader context, following technical, operational and commercial perspectives (Ulstein and Brett, 2009, 2015). The goal of deterministic optimization is to select the best alternative within a set of feasible ones based on a set of criteria (Papanikolaou, 2010). A set of constraints is defined, so some variables are considered as known and kept constant over time. Factors such as market demand and supply, cost of material and other are predefined. Deterministic optimization in ship design has been employed on a holistic view, for a ship as a system but also to specific capabilities of the ship systems such as hull form, operability or survivability (Papanikolaou, 2010).

2.3.2. Delay

Delaying decisions imply the fact of taking the decision to defer a choice in the belief of expecting a higher return by seeking more information or searching for new alternatives (Dhar, 1996). Indecisiveness, delayed decisions or defensive decision-making, is a root of literature relatively immature with regards to behavioural decision making (Stingl and Geraldi, 2017a), although it has been studied in more depth by normative schools. Some examples are concurrent engineering (or design), set-based design, real options, and probe and learn techniques of new product development.

It is not uncommon to arrive at decision situations where none of the decisions is ideal, or where all the alternatives have undesired consequences. The dilemma of choosing an alternative in these situations tends to postpone the decision (Simon, 1987). See the discussion in Section 2.1.7 about the balance of exploration and exploitation activities.

2.3.2.1. Concurrent design – as a means to delay decisions

Concurrent engineering or concurrent design (also defined as simultaneous engineering, integrated product development or co-operative product development) is categorised as a systematic approach for integration and concurrent design of new vessels (Elvekrok, 1997). The product of concurrent engineering is to generate more *hard* information at earlier stages of the design, so critical decisions are not made on *soft*, uncertain information (Mistree *et al.*, 1990). The goal of approaching the problem as concurrent is the reduction of the overall development time. Rather than refining the final vessel design by iterative, sequential learning, design activities are carried in parallel, by interconnecting them. To reduce re-work and corrective engineering, concurrent design explores the most critical elements influencing the vessel design and its future operation in early design phases. Yet, as argued by Smith and Eppinger (1998), concurrent tasking may sometimes increase the total amount of rework, since data, information or knowledge gained during the design process may lead to repeat calculations, thereby increasing engineering effort, and potentially development costs and lead time; making the design process ineffective. In ship design, many tasks are interconnected, stability calculations e.g. depend on the definition of hydrodynamic characteristics, as well as on the estimation of weights and gravity centres. Such interdependency challenges the applicability of concurrent engineering in some stages of the ship design process. One application of concurrent engineering is the *Decision-Based Design* of Mistree *et al*. (1990).

2.3.2.2. Set-based design – as a means to delay decisions

Set-based design (SBD) follows the principles of concurrent design, deferring the detailed specification until more information is available and trade-offs are better understood (Singer, Doerry and Buckley, 2009). SBD is a flexible design methodology allowing continued refinement and integration into the overall design. In set-based design, the design space is explored with several alternatives, eliminating overtime Pareto dominated solutions, focusing on developing further just Pareto Front design alternatives.

Building on the principles of set-based design, Claus and Collette (2018) propose an optimization framework consisting on the reduction of the design space based on two factors, design space complexity and regret of performance loss. The aim of the framework is to reduce the potential design space while minimising the regret of the solution (Claus and Collette, 2018). In other words, simplifying the selection of a vessel design without compromising performance. Unfortunately, the framework seems to be limited to simple problems (Claus and Collette, 2018).

2.3.2.3. Probe and learn – as a means to delay decisions

Lynn, Morone and Paulson (1996) describe the *probe and learn* methodology as a strategy to reduce uncertainty in new product development based on learning. Described as a learning-driven process (Fox *et al.*, 1998), probe and learn consists on probing early versions of the product to learn about market reaction, technology level and so, before a final design is chosen. The decision-maker looks for empirical evidence, by performing low-cost, low-risk and low-distraction experiments (Collins and Hansen, 2011). The purpose of such experiments is then to find actual certainty provided by the empirical evidence (Collins and Hansen, 2011). This approach is followed as well in ship design, where designers or investors show the product to potential customers to get feedback and market potential before the vessel is further developed or build. The entire ship design process can be seen as a probe-an-learn activity in itself. Relying on the sequential description of the design process proposed by Evans (1959), each turn of the spiral is carried out to test some decisions and learn the consequences of them. Fox *et al*. (1998) expand this methodology into what they define as *speed-to-learn*, where the learning curve is accelerated by implementing a probing strategy in a rapid, focused and logical manner.

Alternatively, companies can follow a *wait-and-see* approach, where no decisions are taken waiting for new information to become available. This is a common practice in the shipping industry, where shipping companies wait-and-see for a market recovery before they invest in new vessels (Juliano, 2019). The fast-follower strategy relies on this principle. Rather than being the first moving into one vessel segment, testing new technology or using a new fuel type, fast-followers wait for someone else to try first and based on the results, they can decide what to do.

2.3.2.4. Real options – as a means to delay decisions

The Real Options[4] approach is an extension of financial options theory to options on real - not financial - assets (Borch, 2012). Real options are also denominated life cycle options (Fawcett *et al.*, 2012). A (financial) option is defined as "a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time" (Black and Scholes, 1973, p. 637). Similarly, real options "refer to elements of a system that provide *rights, not obligations* to achieve a goal or activity" (de Neufville, 2003, p. 9). In the context of ship design, real options are described as "managerial decisions aimed to maintain necessary financial performance in reaction to changing circumstances such as fuel price, demand, competition, etc." (Puisa, 2015b, p. 3). Uncertainty and the ability to respond to it (flexibility) are the sources of value of an option (Borch, 2012; Schwartz, 2013). In other words, real options analysis is a methodology for valuing flexible strategies in an uncertain world (Trigeorgis, 1995; Bendall and Stent, 2005; Alizadeh and Nomikos, 2009). Therefore, the number of options a project or design has the more flexible it is (Fawcett *et al.*, 2012).

Financial literature defines two types of options: *call* option (gives the option holder the right to buy an asset in the future) and *put* option (gives the option holder the right to sell an asset in the future). In addition, there is a distinction between European and American option, where the first can only be exercised on their date of maturity, while American options can be exercised at any point before their maturity date (Dixit and Pindyck, 1994). In which regards to real options, there are four major types of options categorised in the literature: option to *expand*, option to *abandon*, option to *postpone* investment and option to temporarily *suspend* production (Borch, 2012; Schwartz, 2013). Small variations in nomenclature are found among different authors and business areas, a brief comparison is included in Table 2-6. Further, Pawlina and Kort (2003) introduce the term of *strategic* option, as the value of being the first-mover in a market, and the associated benefits.

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[4] Terminology introduced by Stewart C. Myers on his journal article "Determinants of Corporate Borrowing" at the Journal of Economics (Myers, 1977).

Real options are important not only for identification and evaluation of investment decision pathways or management in uncertain business environments but also to compare strategic decision pathways and evaluate their financial viability and feasibility (Alizadeh and Nomikos, 2009). In general, three methods can be used to price real options: analytical or closed-form solutions, Monte Carlo simulation and tree model or lattice methodology. The latter method is employed by Bendall (2005) in exploring the value of flexibility on an investment in an express liner service at the port of Singapore. In his exercise, Bendall considers three uncertainty factors, demand for vessel services, dayrates and uncertainty regarding the performance of the vessel as a service element. Among three service alternatives resulting from the combination of two markets and one or two vessels, the alternative of serving the two markets with one vessel was valued as the best option considering the uncertainties characterising the market. The higher value resulted from the flexibility of that alternative. Serving two markets with one vessel gives the possibility of expanding the market to two vessels or constraining it to one market only.

Table 2-6 Brief comparisons of types of real options.

<table>
<tr><th>Investment projects</th><th colspan="3">Shipping</th><th>Building industry</th></tr>
<tr><td rowspan="2">Expand option</td><td rowspan="2">Expand option</td><td>Expand option</td><td rowspan="2">Expand option</td><td>Expand or upgrade option</td></tr>
<tr><td>Contract option</td><td>Contract option</td></tr>
<tr><td>Abandon option</td><td>Abandon/exit option</td><td>Abandon/exit option</td><td>Abandon option</td><td>Abandon option</td></tr>
<tr><td>-</td><td>Switch option</td><td>Switch option</td><td>-</td><td>Switch option</td></tr>
<tr><td>Postpone option</td><td>-</td><td>Delay option</td><td rowspan="2">Wait or defer option</td><td rowspan="2">Defer option</td></tr>
<tr><td>Temporary suspend option</td><td>Lay-up option</td><td>Lay-up option</td></tr>
<tr><td>(Borch, 2012; Schwartz, 2013)</td><td>(Erikstad and Rehn, 2015)</td><td>(Alizadeh and Nomikos, 2009)</td><td>(Puisa, 2015b)</td><td>(Fawcett et al., 2012)</td></tr>
</table>

2.3.3. Reduce / Control

2.3.3.1. Data, information and knowledge gathering- as a means to reduce/control uncertainty

On an organizational level, the most basic methodology for handling uncertainty is the generation of information. Peace Cox (1974) suggest that research should be used for providing information for quality business decision-making, hence, connecting information quality to the amount of information available. Tolpin and Shimony (2012) name it measurement actions. Gathering information and knowledge in organizations is however constrained by three myopic bias (Levinthal and March, 1993): (i) temporal myopia, limited to short-run, time-constrained research; (ii) spatial myopia, limited to literature, information and data available within the own organization, country or with the same language; and (iii) failure myopia, research tends to focus on success stories and not on failures, which makes it difficult to learn from the latter. These three elements limit the effectiveness of learning and its use on handling uncertainty.

Although good research does not necessarily eliminate the uncertainty involved in decision-making, it can prove economically warranted means of at least reducing that uncertainty (Peace Cox, 1974). In the same line, Perminova (2011) states that uncertainties cannot be eliminated in the short term, but through investigations, in the long term, they can be significantly diminished or turned into opportunities. Taghavifard *et al*. (2009) identify a positive relationship between the amount of information and the quality of a decision. The way in which information is presented contributes to its trustfulness and usefulness (Nadelhoffer, 2018) or how Turpin and Marais (2004, p. 149) put it, “Information is a weapon that should be packaged convincingly”. Decision-makers should be aware that information alone does not suffice to reduce uncertainty. Uncertainty is reduced when decision-makers can extract meaning from the information available. To this respect, graphical representations can be used as a key tool to understand uncertainty (Wainer, 2009). Many decision-making situations are surrounded by more information than what necessary to resolve substantive uncertainties (March, 1994). In other cases, the information available is ignored or not properly understood. In situations of time constrain or on critical decisions, the availability of information may overload decision-makers and does not lead to better decisions (Marusich *et al.*, 2016).

Cognitive limitations of human decision-makers limit the gaining that additional information could provide to decision-making processes. Marusich *et al*. (2016) findings suggest that computational decision-making is improved by increasing the availability of relevant information. The same effect could not be proven with human decision-makers. On a study carried out by Paul Slovic, interviewees achieved better results on horse races when they had available only information relating to 10 performance parameters compared to when they were given 20 parameters (Taleb, 2010, p. 145). Their confidence was, however, higher in the second case. Hence, decision-makers shouldn’t look just for information, rather look for the information they consider valuable for the decisions they must face. Here builds the concept of value of information proposed by Garcia *et al*. (2019). A trade-off is required between information to reduce uncertainty and the complexity induced when increasing the amount of information (Gaspar, Hagen and Erikstad, 2016). Schouten (2018) suggests that ship designers spend an excess of 30% of their time searching for information. The author argues that the way data is stored, shared and processed converts the searching of information in ship design an unnecessarily complex activity. Product lifecycle management (PLM) and product data management (PDM) techniques look for better control and structuring of information to solve this challenge and improve the effectiveness of the design process (Maropoulos and Ceglarek, 2010).

Nutt (2007) identifies six approaches for gathering intelligence in decision-making situations: negotiated, rational, problem-solving, opportunity, emergent opportunity and redevelopment. Based on his review of 376 decision situations, Nutt suggests that negotiated and rational searches present the best performances, independently of the degree of difficulty of the decision, and the number of resources allocated. The former relates to the coordination of stakeholders to discuss and uncover options. The latter relates to the use of protocols to reveal alternatives fulfilling the initial needs.

Information regarding the operating environment, the fleet or the customer itself can be of value for ship designers. Today, there are multiple of such databases available for purchase, including information such as: vessel dimensions, vessel capacities, vessel contracting activity, dayrates, etc. Ebrahimi *et al*. (2015) explore the use of marine databases as basis for the conceptual design of offshore support vessels. In their work, Ebrahimi *et al*. use fleet data to estimate main capacities and capabilities of alternative vessel designs in the early conceptual. Other sources of information important for design firms are the annual reports of shipping companies. Information regarding the financial performance of potential customers could be used as a reference for management regarding the prioritization of projects (Ransbotham and Kiron, 2017, 2018).

2.3.3.2. Management and organizational tools – as a means to reduce/control uncertainty

Strategic management is recognised as the "art of dealing intelligently with three main challenges in decision making: ignorance, conflict and ambiguity [here uncertainty]" (Levinthal and March, 1993, p. 109). Hence, management and organizational tools can provide critical, accurate information needed to reduce the level of uncertainty in decisions (Peace Cox, 1974; Cleden, 2009). Related to project management and business decisions, Buytendijk *et al*. (2009) propose the combination of enterprise performance management (EPM) and enterprise risk management (ERM) as ways of uncertainty reduction in business decisions. EPM processes focus on identifying how to take advantage of opportunities and turn them into success for the business. ERM looks at the same opportunities, identifying the impacts on the business and how to deal with them. Similarly, Danilovic and Sandkull (2005) introduce an approach based on the systematic analysis of interdependencies and relations, the design or dependence structure matrix (DSM) and domain mapping matrix (DMM). This approach focus on organizational settings, to achieve a high degree of coordination and integration in problem-solving, considerably reducing uncertainty (Danilovic and Sandkull, 2005). The DSM can be used for modelling how change propagates through a design, mapping functional requirements onto design variables, and studying how the functional requirements may change. Thus, change-sensitive design variables can be identified (Garcia et al., 2016). By finding the largest set of design variables that are not sensitive to changes, designers can formulate a platform design that will be valid under many different functional requirements. A similar exercise is carried out by Hillson (2002), who introduces the double Probability-Impact Matrix, as a tool to understand the relative importance of both opportunities and threats consequence of uncertainties. Most of these tools are coming from risk management literature.

Performance benchmarking is also recognised as a popular managerial tool (Rolstadås, 1995). The use of benchmarking in decision-making situations: (i) supports a quantitative definition of goals, and therefore the elimination ambiguities, (ii) facilitates the identification of factors with most relevance in the outcomes of decision and therefore guides the decision-maker towards what to pay attention to, and finally (iii) facilitates the quantitative identification of what is a better decision alternative. Performance benchmarking is already in use in ship design processes (Ebrahimi, Brett, Garcia, *et al.*, 2015; Ulstein and Brett, 2015).

Although not a management tool, joint ventures, partnerships, vertical integration and joint industry projects are managerial strategies, exploited by firms to, potentially, reduce uncertainty (Miller, 1993). After all, the use of multiple perspectives may neutralize the biases and weaknesses of the individual perspectives (Creswell, 2014). Other tools developed to support more informed, better decision making is (Binda Zane, 2016): SWOT (Strengths, Weaknesses, Opportunities, and Threats) – developed to deal with the inner and outer characteristics of a decision problem, PEST (Political, Economic, Social, and Technology) – used to evaluate all external factors to a decision, TELOS (Technical, Economic, Legal, Operational, and Schedule) – to evaluate the resource availability in a decision, Porter's Five Forces – used to analyse the competition.

Another resource available to designers to reduce uncertainty and support decisions are validation and verification activities (Hu and Paez, 2016). Verification and validation are complementary procedures available to designers and used for checking that a system meets initial expectations and specification and that the system fulfils the intended purpose it was designed for. Both validation and verification are used independently, at different stages of the design process and with complementary purposes. System verification is carried out to ensure that the system fulfils requirements and constraints stated (designing the system right), while system validation ensures the system does what it was supposed to do (designing the right system) (Bahill and Henderson, 2005). Figure 2-19 includes a graphical representation of validation and verification activities as part of the ship design process.

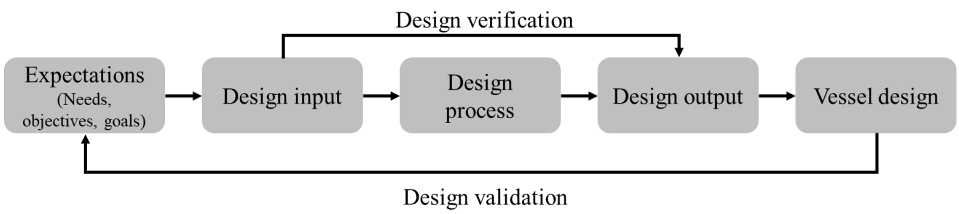


Figure 2-19 Design validation and verification activities. Adapted from (Burlington, 1997).

The early design stages are very important for the correct elucidation of system requirements arising from understanding and interpreting market needs (Maropoulos and Ceglarek, 2010). Requirement validation is essential for designers in these early phases to ensure that they are working on the right set of requirements. The capacities and capabilities of the conceptual design alternatives generated in the early design phase shall be further verified in further downstream activities on basic and detail design phases. Hence, verification is an activity belonging to the specific design domain itself, while validation represents a bridge between the specific design domain and other domains (Veeke, Lodewijks and Ottjes, 2006).

Embracing uncertainty is cited by Matheson & Matheson (2016) as one of the nine principles of smart R&D organizations. Embracing uncertainty, that according to Matheson & Matheson (2016) leads to better results, consist of recognising what it is unknown, and communicating it through the organization. This principle requires a common language to communicate and manage uncertainty. This common language may be probability management, which according to Savage (2012) supports the coherent visualization, communication and handling of uncertainty and risk. By using probability management, decision-makers bring forward uncertainty in their activities. Rather than relying on a single-number reference, uncertainty is communicated by a range of values and potentially, a probability distribution. Hence, when working on a new vessel conceptual design, where the lightweight is communicated as "2 669 tonnes (incl. 3% margin)" could rather be communicated as 2 430 to 2 752 tonnes, where the lower limit reflects vessels built for customers in Region A, and the upper limit vessels built for Region B. This way of communicating uncertainty helps decision-makers to feel a higher control of the information and uncertainty itself, and avoid the withdraws of the flaw of averages (Savage, 2012). Yet, probability only doesn't suffice, and decision-makers should be aware of the causalities behind those probability distributions (Pearl and Mackenzie, 2018).

Standards and the guidelines proposed by classification societies are also means to reduce uncertainty in ship design processes. The ship designer ensures that the structure of the vessel and the thickness of different places will suffice to ensure safe operations with sufficient margins.

2.3.3.3. Scenario planning – as a means to reduce/control uncertainty

Scenario planning is a technique commonly used for planning and decision-making in situations characterised by large environmental uncertainty. In such situations, it is dangerous to assume that current assumptions will be valid over the entire lifecycle of the project or the design life of the product (Moyer, 1996). Some examples of applications are in design projects, such as in the airplane industry (Randt, 2015), strategic planning, like Shell in the offshore oil & gas industry (Schoemaker and van der Heijden, 1992) or British Airlines in the airline industry (Moyer, 1996), and in general decision problems (Chermack, 2004).

The ability to deal with unexpected events depends, largely, on the structures developed before such an event happens (Weick and Sutcliffe, 2007). Scenario planning allows for building alternative stories of how the future may evolve, and subsequently the quantification or evaluation of how different decision alternatives in the present will result in such potential futures. Scenarios are not predictions of the future, neither extrapolations of the past, rather, they represent plausible futures (Chermack, 2004). Schoemaker and van der Heijden (1992), based on their experience developing scenarios at Shell, recommend to define scenarios considering: (i) issues and information of great concern for the decision-makers (select critical issues), (ii) recognised elements of the environment that can affect the outcome of the decisions (identify uncertainties), (iii) trend breakers and (iv) potential surprises. Scenario planning is especially useful with unresolvable uncertainties, or those that could be resolved but is not practical. In such circumstances, rather than spending immeasurable amounts of resources on predicting the unpredictable futures, companies could develop alternative strategies for *what-if* situations.

A similar technique used to study the variability of future context and expectations is Epoch-Era Analysis. This approach structures and visualizes system timelines based on the development of the context and the system expectations (Ross and Rhodes, 2008a). Thus, an Epoch is a period of time where context and expectations are fixed. Respectively, an Era consists of linear accumulation of Epochs representing the full lifespan of the system. Some examples of the application of Epoch-Era in ship design are the work of Keane, Gaspar and Brett (2015), Gaspar, Hagen and Erikstad (2016) or Curry et al. (2017).

2.3.3.4. (Data) analytics – as a means to reduce/control uncertainty

Data analytics consists of the extraction of value from information. Analytics is gaining weight as decision-making support tools in many business organizations which, by use of data, look for analytical insights for strategic purposes, uncertainty reduction and innovation (Ransbotham and Kiron, 2017). The value of such analytical processes relies more on the way of how they are used rather than on the data or the technologies used to analyse it (Davenport and Harris, 2017), although analytics resulting from data of poor quality may not reflect the reality. One application of data-driven decisions in ship design is, as presented by Gaspar *et al*. (2014), on the generation of knowledge for conceptual ship design. Similarly, graphic tools facilitate the decision-making process and lead to better decisions in shipbuilding projects, as argued and exemplified by Mascaraque *et al*.,(2018). Tradespaces (Ross and Hastings, 2005), goodness-of-fit and performance indices (Ebrahimi, Brett, Garcia, *et al.*, 2015) are of good support when deciding what is a better ship (Ulstein and Brett, 2015). A broad overview of the use of analytics in the ship design industry can be found at (Keane *et al.*, 2017).

Norwegian shipping companies recognise the value and agility that digitalization could provide to their decision-making and business models, and how data analytics could support better resource utilization and the optimization of ship operations (NSA, 2018). Similar conclusions were drawn from a worldwide survey (UBM, 2018), which identified investment costs as one of the top weaknesses of data analytics and digitalization. Nutt (2007) suggests that although time-consuming and potentially costly, data collection and analytics have a considerable payoff when used as support in decision-making. Most recently, Stena Line has started the implementation of Artificial Intelligence (AI) algorithms as a decision support tool for captains and officers of the fleet with the main purpose of reducing fuel consumption and minimise the impact on the environment. The algorithms will simulate a variety of scenarios, including alternative routes and propulsion configurations, to suggest the most favourable alternative to the crew (Dixon, 2018). Clustering may also be used as a technique to reduce uncertainty (Taleb, 2010). By associating elements to a cluster, we incite that they share a set of commonalities, therefore in the event of unknown information relating to the member of a cluster, it could be assumed based on the information available from the other members of the cluster.

One side of analytics is statistical analysis. Statistics have been part of the science of uncertainty since the era of Jacob Bernoulli (1654-1705), and represent an aid navigating through uncertainty (Wainer, 2009). The use of statistical data for predictions should be considered with special consideration. Statistics can be a powerful tool to reduce uncertainty and support more informed decision-making but can also lead to decisions taken under erroneous information. Taleb (2010) suggest two types of factors, *mediocristan* – those that can be predicted based on historical data, and *extremistan* – those that cannot. Yet, even with mediocristan factors, the use of statistical data for predictions requires a structured process to avoid misuse of statistical relevance (Hair *et al.*, 2010). Kahneman (2011) suggests three steps to follow when using statistics in forecasting: (i) identify an appropriate reference class (sample, period of time, etc.), (ii) extract statistics from the reference class and define a baseline prediction, and (iii) use specific information about the case study to adjust the baseline prediction.

A simple example of real projects is the estimation of the newbuilding price for a new vessel. In many cases, and based on statistical information, the price of a newbuild can be estimated with relative accuracy based on a handful of parameters: newbuilding country, steel weight, vessel type, installed power and type of special equipment. Ship design practitioners are however very sceptic about the use of such simplistic approaches. There is one major aspect behind such scepticism: the number doesn’t correspond to an accumulation of costs. Shipyards and ship designers are used to talk about vessel prices as the accumulation of element costs: ten million for the hull, three million for the design, two million more for each engine, etc. Prices calculated based on statistical data do not represent accumulations. Although they can be related to the main dimensions and capabilities of the vessel, they are not subdivided into the same elements than traditional vessel pricing. This is an aspect difficult to come about. Thus, if people can’t relate to what they know, they will not trust analytics. However, the use of analytics given a major potential for simplification of tasks like pricing at early stages where accuracy and risk-taking are not essential, but price orientations are vital for the further development of the project.

2.3.3.5. Simulation – as a means to reduce/control uncertainty

Simulation is a technique for reducing uncertainty by means of understanding and predicting the behaviour of a system (Simon, 1996). Simulation techniques in ship design have been spurred by the expansion of computational power (Nowacki, 2010). This methodology has been integrated on optimization models pursuing, in most of the cases, the maximization of the economic performance of the vessel design. An overview of optimization analyses has been collected and compared by Nowacki (2010). Wynn, Grebici and Clarkson (2011) explore simulation techniques in design under uncertainty, arguing that simulation techniques could be used as a technique to reduce critical uncertainties and improve the performance of the process. Further, Balaban and Mastaglio (2013) propose modelling and simulation (M&S) techniques as decision-support aids to managerial decisions in the RoPax & RoRo market. A similar exercised was carried out by Garcia *et al*. (2018), who explore simulation techniques to quantify the consequences of uncertainty in the economic performance of factory stern trawlers. Simulation techniques are however limited by the assumptions built into it (Simon, 1996). It is, therefore, paramount to understand the assumptions of a simulation model to be aware of the limitations on the results.

2.3.3.6. Prototyping – as a means to reduce/control uncertainty

Prototyping it is considered to be one of the most powerful tools of managers and designers to reduce the uncertainty of new product developments (Lund Strøm *et al.*, 2018). Prototyping gives the designer the opportunity of testing his or her ideas and explore the functionality of a system in practice (Ambrose and Harris, 2010). Thus, the use of prototypes is of special value for validation of requirements (Sikora, Tenbergen and Pohl, 2012). In design thinking, prototyping is seen as one of the central steps in the design process (Buede, 2009).

Although most of the literature refers to physical prototypes, there exist substantial benefits from digital or virtual prototypes. In many industries, physical prototyping is still a requirement, although digital alternatives are becoming more common (Maropoulos and Ceglarek, 2010). Virtual prototyping brings the possibility of simulating changes during design or operational phases of systems before their real implementation. In ship design, they are used frequently to test the performance of the vessels before they are built, as a way of ensuring system performance (Keane *et al.*, 2017). The use of physical prototyping in the shipbuilding industry is limited. Outside prototypes of onboard elements such as pumps or engines, it is not practical to develop full scale or partial scale prototypes of a vessel before this is built. The principal reasons for this are the cost of building a vessel and the fact that there is no mass production of units. Tank tests are a version of prototyping used extensively in shipbuilding. A scaled model of the hull is tested on a controlled environment to predict the resistance of the vessel and its seakeeping performance before the vessel is built.

2.3.3.7. Communication – as a means to reduce/control uncertainty

Brashers (2001) describes the importance of communication management in the overall uncertainty management strategy, looking beyond the uncertainty reduction paradigm. Uncertainty may arise from the own perception of understanding, or the ability to derive knowledge from the information available (Brashers, 2001). Uncertainty can also arise from the interaction between different entities, human-human or machine-human, both at personal or organizational levels. In some fields, each institution, speciality, or technical discipline may have its own unique language and jargon. Broniatowski *et al.* (2009) recommend the use of specialized technical words, symbolism, both written and oral language as a means to encapsulate and transfer knowledge avoiding the subjective meaning of using other ambiguous terminology. On the other hand, this symbolism may challenge communication within interdisciplinary groups. An example of the importance of handling such uncertainty in projects is the software Gamalon. This software recognizes uncertainty and ambiguity in text and predicts the meaning of certain words building on artificial intelligence (AI) (Knight, 2018).

2.3.4. **Accept / Protect**

Ship designers have been incorporating measures and strategies for protecting the vessels and preparing them for future uncertainties for a long time. Unfortunately, in most cases, this has been done in an unstructured manner; in other words, they are not institutionalized (Doerry, 2014).

2.3.4.1. Adaptive control strategies – as a means to accept/protect against uncertainty

A popular technique of adaptive control in ship design is the use of digital twins. A digital twin is a model capable of rendering the state and behaviour of a unique real asset in (close to) real-time (Erikstad, 2017). Digital twins allow the monitoring of a real asset to prevent damage to the system and ensure efficient operations, this capability is referred to as adaptive control. For example, rather than adding a 5 or 10% margin in the strength of the hull, we can measure the strength at any time and take preventive measures when the level is close to the maximum. Similarly, digital twins allow us to simulate the consequences of decisions before those are implemented in the real asses, reducing, therefore, the final uncertainty.

2.3.4.2. Margins – as a means to accept/protect against uncertainty

The most common way to handle uncertainty in ship design processes today is by adding margins and/or safety factors, in order to ensure a minimum performance level (Meyer, 2002). Safety factors are used by designers "to allow for what we [as designers] don't know" or are uncertain about (Waldrom, 1992, p. 60). This practice derives from risk management and has some limitations as stated by Haugen and Vinnem (2015). Considering the intrinsic uncertainty present in ship design and in the future operation of the ship is unpracticable to protect the design process and the vessel with margins against all possible events, especially considering that many of them are unforeseeable. Further, uncontrolled use of margins, in order to protect the design against what could go wrong, or prepare for future needs, could easily lead to uncompetitive ship design solutions. For example, excessive hull strength will increase the weight of the vessel (Garcia *et al.*, 2016), hence reducing the performance and increasing the costs. A 5% steel margin on a 3 000 tonnes vessel would represent an additional investment of $750 000 ($5 per kg of steel).

Because of the importance of margins in the performance, cost and safety of the vessel design, among others, they have to be carefully managed during the design process (Brahma and Wynn, no date). Margins appear either explicitly in their calculations and decisions or implicitly when applying rules and regulations or considering the information provided by the suppliers. Vrijdag, de Jong and van Nuland (2013) describe the use of margins in the calculation of the bollard pull in tugs. This challenge is also present in other design situations, like aircraft design, where excessive use of margins would lead to unnecessary use of material and consequently detrimental extra weight (Hernandez *et al.*, 2012).

One of the most important challenges in design practice is avoiding unnecessary addition of margins (Gale, 1975). Every stakeholder in the value chain introduces their own margins with different purposes (Meyer, 2002): (i) account for uncertainties in the design methods (accuracy of calculations); (ii) assure safe operations, even after degradation of vessel components; (iii) assure performance even if operating conditions are slightly different from those which the ship was designed for; and iv) allow for future changes. With this consideration, Eckert and Isaksson (2017) differentiate between *safety margins*, used to cater for uncertainties of use, and *design margins*, to cater for changes in requirements or engineering. Safety margins are included in design requirements for dealing with known risks, while design margins are added to design parameters to deal with uncertainties. A similar differentiation is proposed by Jones and Eckert (2017), who consider margins relating to regulatory, clinical and contractual requirements and margins in engineering design choices to cater for contingencies and uncertainties.

The importance of properly applied and assessed margins in ship design was early stated by the US Navy. In the mid 70', the studies of Hockberger and Gale (among others) addressed the use of margins and their consequences (Gale, 1975; Hockberger, 1976). Hockberger classifies ship design margins in three categories: design and construction margins, assurance margins and future growth margins. A similar categorization was proposed by Garcia *et al*. (2016a) in relation to the commercial merchant and offshore ship design, including: (a) design and construction margins**:** margins introduced in order to treat the uncertainty present in the early stages of the design process. A typical example could be the steel weight or the speed performance of the vessel; (b) life-cycle margins**:** margins introduced in order to account for future events and degradation of the systems. Some examples are sea margins or future-growth margins, and (c) market margins**:** margins introduced for commercial purposes. A common practice in order to increase the second-hand value or as a differentiating factor over the vessels' lifetime. The implementation of such margins should pursue a commercial purpose and utility value. A typical example could be an increased DP (dynamic positioning) capability or excess use of steel in an offshore vessel to extend its lifetime and overall robustness in use.

An overview of the cumulative effects of margins in ship design is presented in Figure 2-20.

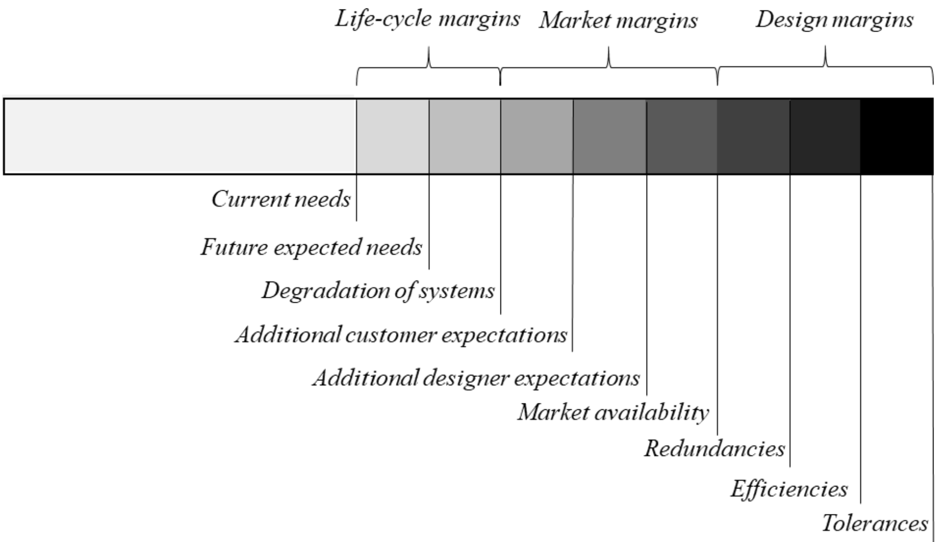


Figure 2-20 The cumulative effect of margin concepts. Adapted from (Eckert, Isaksson and Earl, 2019, p. 13).

In contrast with the distinction proposed by Eckert and Isaksson (2017), design and construction margins represent what are categorized as safety factors, while life-cycle and market margins would be design margins. Margins, both related to design and safety, are added by the different departments or stakeholders along with the design and construction value chain. Misinterpretation or miscommunication could lead to duplication of margins or to the elimination of purposeful margins. Therefore, the addition of margins, if not well managed and communicated may not have the intended result. A common example of the lack of correct margin communication in ship design is review in the following paragraph.

The initial estimate of resistance for a new vessel design has, typically, an associated uncertainty, thus it is common to add a 5% margin to this estimate. The hydrodynamic department sends its prediction to the system integrator department, which assigns an engine and propulsion layout. This shall include sea margin (+15%) and margins regarding the uncertainty in estimating the efficiency of the different elements in the propulsion system (~+5%). The specification of the vessel moves on to the purchasing department which will identify an engine matching the specification. However, there is not an engine for every step of 1 kW, so the selected engine maybe 100 kW above the specified criteria, hence one additional margin (a 5% on a 2000kW engine). Consequently, a vessel with an initially estimated power need of 1 500 kW, will be provided with an engine of 2 000kW. Thus, the vessel will operate for a considerable time of its lifecycle with 33% additional power and the negative consequences it has associated – fuel consumption wise, cost-wise and weight-wise.

2.3.4.3. Resilience – as a means to accept/protect against uncertainty

Resilience is defined as "the ability of a system to recover and return to a new stable situation after an event disrupts the normal operation of the system" (Pettersen and Asbjørnslett, 2016, p. 2). Resilient systems are characterised by the minimization of the loss of performance, disruption time or recovery cost after a disruption has occurred (Pettersen, 2018). A resilient system will, therefore, recover its performance (totally or partially) after a disruption. Redundant systems are designed in a way that critical systems are duplicated, so in case of failure of one of them, the duplicated system can cover the demand. Pantuso, Fagerholt, and Wallace (2016) suggest that large fleets are more resilient to uncertain events because of the flexibility gained by having a higher number of vessels. Latency may be seen as a strategy for building resilience into systems (Pettersen, Erikstad and Asbjørnslett, 2018). The main difference between latency and resilience is the fact that the latter is a purposeful activity. Latency, contrary to redundancy, considers that in case of a disruption, an alternative system, that was not intentionally designed for, can deliver the uncovered demand.

2.3.4.4. (Passive) robust design – as a means to accept/protect against uncertainty

Value robustness, as the quality of a system to deliver value over a variety of contexts and needs, can be achieved via *active* or *passive* means (Ross, Rhodes and Hastings, 2008). Value robust designs are characterized by a lower value sensitivity to variations in the context. A value robust ship is "the one able to bring a return on investment (RoI) in face of the uncertainty of missions that this ship may encounter during its operational lifespan" (Gaspar, Hagen and Erikstad, 2016, p. 17). Passive value robustness strategies pursue the incorporation into the initial design of evolving features, such as requirements or Regulations, even though they are not fully known at the time (Doerry, 2014). Contrary to active value robustness, passive value robust designs do not consider changes in the system after built. Passive value robustness can be related to the use of market and life-cycle margins. However, value robustness has a price (Bertsimas and Sim, 2004). In value robust ship, the shipowner is willing to accept a sub-optimal operation of the vessel in one particular context, in order to ensure that the vessel can operate near to optimal if and when the contextual factors or other uncertain factors change. The dynamic positioning (DP) classification criteria rely on this principle. A DP 2 vessel has to keep a set of pre-defined redundancies. This set is stricter for DP 3 vessels. The risk of value robust designs is that they may be too conservative (Bertsimas and Sim, 2004) and influence, critically, and negatively the performance of the vessel over its entire lifecycle.

The concept of robustness could be seen as an expansion of reliability, see Figure 2-21. While reliability relates to the ability of a system to deliver a given performance on a set of circumstances. Robustness expands the set of circumstances to include uncertainty in them (Chalupnik, Wynn and Clarkson, 2009). Yet, as shown in Figure 2-21, uncertainty may also relate to the expectations of requirements for a system. Therefore, in the case of stable or changing circumstances (domain or context), the features defining the value provided by a system may change. In such circumstance, the system may be designed with such additional features, versatile or multifunctional design, or it may be prepared to be adapted to them, flexible, changeable or adaptable design. The former is what is here considered as *passive* value robustness while the latter is considered as *active* value robustness.

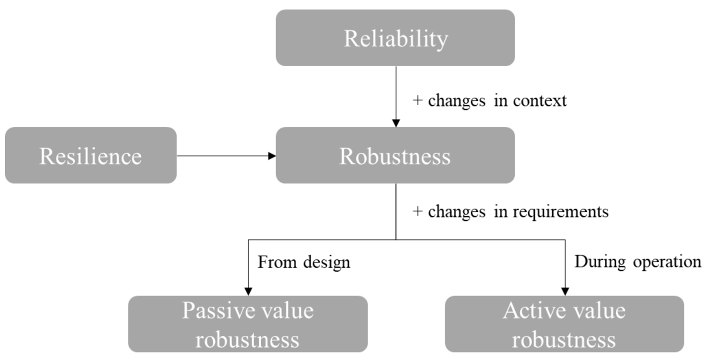


Figure 2-21 From reliability to passive and active value robustness. Adapted from (Chalupnik, Wynn and Clarkson, 2009).

Multifunctionality is another strategy to characterize passive value robust designs (Curry *et al.*, 2017) and it has already been studied and exploited in ship design (Rahman, 2013). Veenstra and Ludema (2006) suggest that versatile ships may be preferred in markets characterized by seasonal, volatile or irregular demand. A collection of industrial cases from versatile and multifunctional vessels can be found in Rehn and Garcia (2018). Versatility and multifunctionality have also been explored at a fleet level (Pettersen and Asbjørnslett, 2016), and many large shipping companies have integrated this concept on their strategy, combining onshore facilities and a versatile fleet to reduce the negative effects of uncertainty (Subsea 7, 2017).

2.3.4.5. Optimization under uncertainty – as a means to accept/protect against uncertainty

Problems of optimization under uncertainty rely on the fact that uncertainty is intrinsic in decision-making, especially those decisions relating to long-term plans (Kwakkel, Haasnoot and Walker, 2016). Decisions have to be taken without a full understanding of the consequences. In such situations where deterministic uncertainty cannot represent the reality of the decision context, decision-makers can rely on stochastic optimization models where uncertainties are modelled as random variables. Optimization techniques are often categorised as *wait and see* or *here and now*; depending on the decision variables, objectives, and constraints. The former represents the optimization of a decision based on probabilistic objectives and constraints, while the latter represents a deterministic case. Some authors identify a third category named *chance-constrained optimization* (Diwekar, 2003). In optimization models under uncertainty, the variables are given probability distributions based on statistical data, or on subjective interpretations that will be modelled into the optimization problem.

When developing the stochastic or dynamic models, one should keep in mind that the complexity of the model will also increase the complexity of the optimization process. Such a demanding situation will require a compromise between accuracy and included complexity. This dilemma is accentuated even further considering that it is not possible to model accurately anyways (Bradley, Hax and Magnanti, 1977; Erikstad and Rehn, 2015). One application of dynamic programming is the *Markov decision processes* (MDPs), where the mathematical concept of Markov chains is integrated into a dynamic programming framework. Markov decision processes have had a positive reception in the shipping industry since the introduction of the ship-centric Markov decision process (SC-MDP) by Niese and Singer (2013). Today, this instrument has been used for long-term strategic decision-making, and as guidance during the design process to gain a better understanding of the consequences and implication of design decisions (Kana and Harrison, 2017). The most recent applications relate to the uncertainty surrounding the implementation of new Regulations, such as ballast water treatment systems, and NOx and SOx emissions (Niese and Singer, 2013; Kana, 2017; Kana and Harrison, 2017). An inference from all these publications can be the fact that the ship-centric Markov decision process is more a tool to generate insights into the decision problem, more than a methodology to select an optimal decision.

2.3.4.6. (Active) robust design – as a means to accept/protect against uncertainty

Active value robustness represents the capability of a system to generate value to its user in changing contexts and requirements by means of adaptation. This capability to change is what differentiates active value robust designs from passive value robust designs. Changeability represents the ability of a system to change (Ross, Rhodes and Hastings, 2008). Change can be related to different aspects of a system, such as form, function or operation. A variety of terms have surged, under the umbrella of changeability, to describe more specifically the type and characteristic of the change. Some of those are: flexibility, adaptability or modifiability, among others (Rehn, 2018). Rehn, Pettersen, *et al*. (2019) propose the use of "Design for Changeability" (DFC) as a design variable in engineering system design. The designer can then specifically select a design given a capability to change its function and form. This capability gives the designer the control of selecting how changeable a design should be, based on the level of changeability and the time and cost of future changes.

Rehn *et al*. (2018) compare the profitability of versatile designs (passive value robust design) and changeable designs (active value robust designs) in the offshore construction market. Assuming uncertainty regarding oil prices (which drives the demand of the market), market competition and the future role of renewable energies and decommissioning of offshore oil & gas facilities; their findings suggest that retrofittability can be of significant value for offshore vessels, especially those operating in long-term contracts. For short term contracts, it is less obvious which strategy is better, versatile or changeable designs. In this case, time to change has a larger effect on the goodness of changeable designs, since there may be not available yards to do the changes when it is required to. Their findings are in line with the current situation of the Anchor Handling Tug Supply (AHTS) market in the North Sea. Table 2-6 includes an overview of the capabilities of the AHTS fleet operating in the North Sea, differentiating between those operating in the spot market (short term contracts) and term market (long term contracts). The data in Table 2-7 is from AHTS vessels involved in spot and term contracts in the North Sea between 01.07.2013 and 30.06.2018. Reading from the table, in general, vessels in the spot market have higher functionality than those in the long-term market. Almost all the vessels in the spot market have DP 2 class, while only 56% of the vessels in term contracts has it. In terms of passenger capacity and ROV capabilities, vessels in the spot market show higher capabilities. On the other hand, fire-fighting (FiFi) capability and oil recovery that in many cases are requirements for long-term contracts are more common among vessels operating in the long-term market.

Table 2-7 Overview of capabilities of AHTS operating in the North Sea.

	DP capability		FiFi capability		Helideck		Survivors		Passengers		Oil recovery		ROV unit(s)	
Spot	No DP	5%	No FiFi	70%	Null	8%	Null		< 40	32%	Null	2%	Null	
	DP 1	4%	FiFi 1	19%	No	92%	No	96%	40 to 59	20%	No	76%	No	41%
	DP 2	91%	FiFi 2	11%	Yes	0%	Yes	4%	>60	48%	Yes	23%	Yes	59%
Term	No DP	29%	No FiFi	55%	Null	11%	Null		< 40	55%	Null	5%	Null	
	DP 1	16%	FiFi 1	32%	No	87%	No	80%	40 to 59	14%	No	67%	No	83%
	DP 2	56%	FiFi 2	13%	Yes	1%	Yes	20%	>60	28%	Yes	29%	Yes	17%

During the years, researchers and practitioners have explored several strategies to improve the flexibility of system designs, and facilitate its changeability by means of modularity (Baldwin and Clark, 2002; Doerry, 2014), standardization (Abrahamsson, 2002) and containerization (Levander, 2007). Time and cost of change are essential parameters in this discussion. At the end of the day, the decision of whether to prepare the design for future changes depends on the probability and value assigned to realizing such changes to the vessel design.

2.3.4.7. Fuzzy decision support systems – as a means to accept/protect against uncertainty

Fuzzy logic systems are used in a variety of applications, among them, as support for the quantification of uncertainty in decision support systems (Salaken *et al.*, 2017). Fuzzy decision support systems produce a *crip* decision and a confidence interval to that decision. Type-2 fuzzy systems, provide an output in the form of an interval, capturing the uncertainty in the process. The interval is the result of the outputs achieved based on the uncertainty of the inputs. The crips value is given by taking the average of the two extreme values (Salaken *et al.*, 2017). An example of applicability could be in the early estimation of steel cost for a newbuilding. Rather than giving a unique value (which in most of the cases will include a margin of 3 to 5%), the designer could express the result based on an interval and a crip value. Assume that the calculated steel weight is 5 000 tonnes and the price of steel plates is between 460 and 510 $/tonne. In a traditional newbuilding context, the steel price may be given as 2.55 mill $ (based on the highest price of steel plates) or as 2.50 mill $ (as the average price of steel plates plus a safety margin). Rather, following the reasoning of a type-2 fuzzy system, the steel price for the new design is given as between 2.3 and 2.55 mill $, with a crip value of 2.42 mill $.

A summary of all the uncertainty handling strategies is included in Table 2-8.

Table 2-8 Summary of uncertainty handling strategies.

	Strategy	*Reference*	*Description*
Ignore	Deterministic optimization	(Papanikolaou, 2010)	Select the best alternative within a set of feasible ones based on a set of criteria and constraints
Delay	Concurrent-engineering	(Mistree *et al.*, 1990)	Design activities are carried in parallel
	Set-based design	(Singer, Doerry and Buckley, 2009)	Deferring the detailed specification until more information is available and trade-offs are better understood
	Probe and learn	(Lynn, Morone and Paulson, 1996)	The decision-maker looks for empirical evidence, by performing low-cost, low-risk and low-distraction experiments
	Real options	(Black and Scholes, 1973)	Real options analysis is a methodology for valuing flexible strategies in an uncertain world
Reduce control	Data, information, knowledge	(Peace Cox, 1974)	Information gathering can prove economically warranted means of at least reducing that uncertainty
	Managerial tools	(Levinthal and March, 1993)	Management and organizational tools can provide critical, accurate information needed to reduce the level of uncertainty in decisions.
	Scenario planning	(Schoemaker and van der Heijden, 1992)	Scenario planning is a technique commonly used for planning and decision-making in situations characterised by large environmental uncertainty
	Data analytics	(Nutt, 2007)	Analytics is gaining weight as decision-making support tools in many business organizations which, by use of data, look for analytical insights for strategic purposes, uncertainty reduction and innovation.
	Simulation	(Simon, 1996)	Simulation is a technique for reducing uncertainty by means of understanding and predicting the behaviour of a system
	Prototyping	(Buede, 2009)	Prototyping gives the designer the opportunity of testing his or her ideas and explore the functionality of a system in practice
	Communication	(Brashers, 2001)	Communication is a critical element in the reduction of uncertainty. The use of specialized technical words, symbolism, both written and oral language as a means to encapsulate and transfer knowledge avoiding the subjective meaning of using other ambiguous terminology
Accept and protect	Adaptive control strategies	(Erikstad, 2017)	Digital twins are one example of adaptive control systems. They allow us to simulate the consequences of decisions before those are implemented in the real asses, reducing, therefore, the final uncertainty
	Margins	(Meyer, 2002)	The most common way to handle uncertainty in ship design processes today is by adding margins and/or safety factors, in order to ensure a minimum performance level
	Resilience	(Pettersen and Asbjørnslett, 2016)	A resilient system will recover its performance after a disruption. Redundant systems are designed in a way that critical systems are duplicated, so in case of failure of one of them, the duplicated system can cover the demand
	Passive value robustness	(Doerry, 2014)	Passive value robustness strategies pursue the incorporation into the initial design of evolving features which cannot be easily predicted
	Active value robustness	(Ross and Rhodes, 2008b)	Active value robustness represents the capability of a system to generate value to its user in changing contexts and requirements by means of adaptation. This capability to change is what differentiates active value robust designs from passive value robust designs
	Fuzzy decision support	(Salaken *et al.*, 2017)	Fuzzy logic systems are used in a variety of applications, among them, as support for the quantification of uncertainty in decision support systems

2.4. Ship design

The shipping industry has played an important role in the global economy over the past 5 000 years (Stopford, 2009). From the wooden boats used by the Scandinavian Vikings, passing by the galleons of Columbus until the advanced cruise ships giving entertainment to more than 6 000 people, ships have been built and operated with the purpose of generating business. Business is generated based on some needs of the market to be met. Ships, technology and customers change, but the basic principles of maritime commerce seem immutable. After 5 000 years shipping continues being a business driven by the laws of supply and demand (Stopford, 2009).

Shipping is an integral part of the process of globalization, which makes it strongly dependent on world economic behaviour. As such, the industry is influenced by factors such as economy, trade, production, consumption, politics, financing and technology that drive the demand and supply of manufactured goods, raw materials and shipping services (Kalgora and Christian, 2016). As described by Stopford (2009, p. 47) “Shipping is ultimately a group of people – shippers, shipowners, brokers, shipbuilders, bankers and regulators – who work together on the constantly changing task of transporting cargo by sea”, or performing special missions in the marine environment such as that of offshore vessels and naval ships. The industry is then surrounded by an intrinsic uncertainty, including volatility of fuel prices, unpredictable demand, ambiguous collaborative and competing arrangements and driven by changing Rules and Regulations. Such uncertainty may be the reason of why many shipping companies make viable business from it (Nordhaug and Hammer, 2018), as many do from the uncertainties of the stock market, but it requires firm and clear decision-making strategies. Taleb (2010, p. 206) suggests that “most of the successful business are precisely those that know how to work around inherent uncertainty and even exploit it”.

Overall the shipping industry generates $650 billion yearly and carries around 90% of the world trade in terms of weight (Stopford, 2009). At the end of 2018, there was 142 000 vessels in operation and 5 700 (4%) on order of a certain size (>100 GT) (IHS Fairplay, 2018). The shipping activity is complemented by a logistic chain that connects the vessel to the land distribution of products and passengers through ports, and the shipbuilding industry. The shipbuilding industry, which generates annually around $175 billion, is kept busy by the shipping industry. The shipbuilding industry has two major roles: one is to give repair and maintenance services to the fleet in operation, and second, support fleet growth and renovation. Over the last 10 years, the fleet has grown, on average, 1.8% y-o-y.

Vessel contracting activity is characterised by its cyclicality. Figure 2-22 reflects a consequence of this behaviour in the development of shipbuilding activity. Two major shipbuilding cycles are identified in Figure 2-22. Shipbuilding activity duplicated its output in the late 60s. The annual production grew from less than 1 000 vessels in the early 60s to more than 3 500 vessels in the late 60s. This higher activity levels remained until the early 80s when supported by a global recession, shipbuilding activity dropped to under 2 500 units. A second cycle took place in the late 2000s, where shipbuilding activity reached close to 5 000 units delivered. This second cycle, contrary to the one taking place in the 60s was substantially shorter. Peak activity lasted for only 4 years. The industry is currently in a recession reaching historically low activity levels.

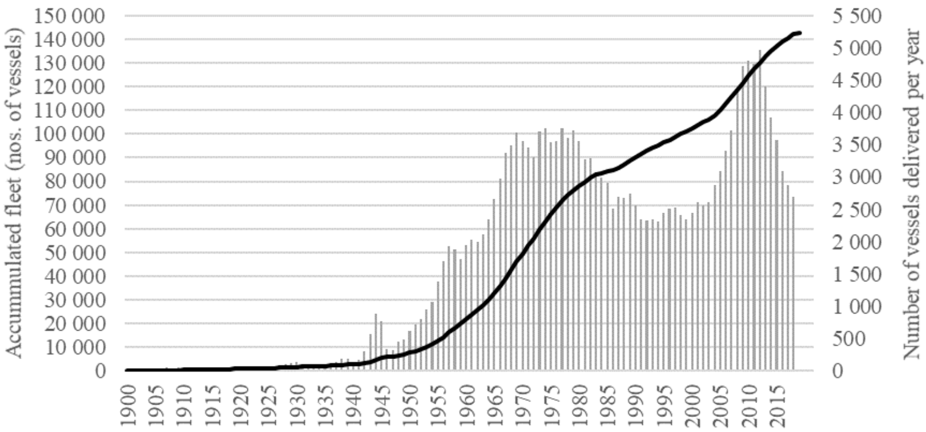


Figure 2-22 Worldwide fleet development and vessel deliveries (1900-2018). Data from (IHS Fairplay, 2018).

The volatility and cyclicality of the contracting activity are reflected in the performance and development of the shipbuilding industry. As an example, the second newbuilding cycle described in the previous paragraph (2008 – 2012) incentivized the construction of more than 350 shipyards in China, out of which more than 70% were already depleted by 2018 (Gourdon, 2019).

2.4.1. Ship design – the industry

The ship design industry is an industry on the edge between a product-based business and a service-based operation. Ship designers sell their competence and knowhow to a customer for developing a virtual product, a ship design configured by a set of design drawings, specifications and analyses reports. The ship design becomes a product when it is finally built and delivered. The services include, in many cases, product-related patents, such as Ulstein's X-Bow feature (Kamsvåg, 2011). Traditionally, the ship design activity was integrated into the shipyard or its function was carried out by the technical department of the shipping company (Branch, 1988). Today ship design firms are more common and present around the world.

Ship design companies work principally following three business concepts when developing conceptual designs: (a) open tenders, (b) closed tenders and (c) front-end engineering design contracts (FEED). In open tenders, typically, the ship design company develops a *no-cure-no-pay* conceptual vessel design, in competition to other design firms, based on a given set of expectations. In this case, the ownership of the ship design is retained by the ship design firm. The concept design of each designer is priced at one or multiple yards, and the design and its related newbuilding price are submitted to the ship owning company for evaluations and discussions – maturing as to be built or not. The ship owning company will select one of the designs, and after final clarifications, sign a newbuilding contract with the yard. Here, the ship designer will act as a supplier to the shipyard, by providing detailed drawings and sometimes technical support during construction. The closed tender concept follows the same procedure, but in that case, only one designer is involved in the process. In the FEED contract, the ship design firms are paid in advance to develop a conceptual design for the ship owning company. In this case, most often, the ownership of the ship design is transferred to the shipowner/buyer.

There are two major differences between the first two business arrangements and the FEED contract: (i) payment in advance and (ii) ownership of the design. The FEED contract ensures that the work performed is paid for, however, this is normally on the expense of the ownership of the design. Since the design was carried out based on a paid-for basis, the owner has the rights to the design, and the ship designer cannot normally sell it to other customers. This can, however, vary from case to case. In some cases, the shipowner only gets ownership of a specific variant of a design, so the ship design firm can still sell a modified version of that design to other customers. On the other hand, in open and closed tenders, the designer does not have secured payment for the work it is doing. In closed tenders, the payment is left to the likelihood of the shipping company to sign a newbuilding contract. In open tenders, the payment is further subject to the likelihood of being the selected designer.

Based on the peculiarity of how the conceptual ship design business is carried out, ship design firms have to focus on reducing the use of resources during the conceptual ship design phase to: (i) reduce the expenses from no paid-for projects, and (ii) increase the profit from paid-for projects. Hence, the profitability and competitiveness of ship design firms will rely, to a large extent, on how effective is their conceptual design process. Competent personnel and their know-how are a critical resource in a design project (Erichsen, 1989). As in any cost-driven industry, the ship design industry is challenged by international competition (McCartan *et al.*, 2014). Norwegian designers and European designers, in general, cannot compete on more commodity-type designs, like bulkers, tankers and container vessels, with other less cost-intensive countries. The hourly engineering cost in Norway is around 670 NOK/hour, compared to 360NOK/hour in Poland and even less in China and Turkey, which are strong contenders. Therefore, in order to compete in price, Norwegian designers must perform the design work in 55% of the time spent by a Polish design firm. The comparison with China is even more drastic. However, competent personnel without the right information or the right tools cannot come too far. Considering that almost all the companies have the same software and the knowledge base, it is up to the way they carry out the process and the strategy to select and manage projects that will define their profitability. Ulstein and Brett (2009) described the need to incorporate flexibility, innovation, speed and agility to the business model, in order to succeed in today's hypercompetitive environment. These five factors are strongly present in ship design companies, especially in the European market, and they influence the way naval architects behave and act in their daily working procedures (van Bruinessen, Hopman and Smulders, 2013).

Ship designers have relied on multiple strategies to achieve this reduction of resources used and make more effective their operations. Many have been the proposals from academia and practitioners to increase the effectiveness of the design process, from the design spiral of Evans (1959) to the decision-based design of Mistree (1990) or the accelerated business development of Brett (2006). Alternatively to the reduction of resources on a single-vessel project basis, the ship design industry has proposed alternative strategies to share development costs among more than one vessel. One example is the development of standardized to order solutions (StO) proposed by Ulstein and Brett (2009) or modular vessel design (Doerry, 2014).

The European shipbuilding industry (including yards and designers) has, in recent years, focused on *one-of-a-kind* projects, where each ship design is modified, adapted and developed for a specific client (van Bruinessen, 2016). In more generic, larger-volume market segments like general cargo vessels, bulkers, tanker or container vessels, it is more common to see larger series of vessels. In these segments, Standardized-to-Order (StO) designs are more easily accepted. One of the reasons is the lower complexity related to those segments. Standardized to order designs have been developed also for smaller-scale industries but still dominated by one-of-a-kind designs. The development of StO designs allowed Ulstein to sell up to 30 units of the PX121 design and 29 units of the PX105 design. However, even being built under the same design name, variations in installed power, number of berths and propulsion system, among others, are found when studying the vessel series in detail.

On a project-to-project basis, ship designers can choose between three strategies in tender or FEED contracts: (1) repeat of an existing design, (2) modify an existing design, (3) start a new design from scratch. The resources spent will depend to a large extent on what strategy they to choose to follow. For this reason, Lamb (2003) suggests that the conceptual design phase can take from 4 and up to 80 man-days. Hence, if the designer chooses to use an existing design as it is, the need for resource spending in developing them is reduced, and only minor work is needed. Change company name, update document date, and maybe changing the colours of the 3D rendering are adjustments typically being done, but at minimal use of cash and re-design resources. If modifications to the existing design are required, more resources will be needed. If changes are minimal, only the GA and 3D model will be adjusted. However, if critical changes are made, the design may require a new round of hydrodynamic and hydrostatic calculations to verify stability and hydrodynamic performance. If the design is developed from scratch, the designer has to establish a completely different marine platform. define a new design strategy and explore the design space, verify the business case and initiate drawings and calculations. The selection of what strategy to follow in each project has to be balanced on one side by the availability of project-related information, resources and the availability of relevant existing designs; and on the other side, by the likelihood to win the project and the value creation of that particular project. Hence, the willingness to spend resources on a three or more-sister vessel project with an existing customer may be higher than a one vessel project with a new customer. The same applies when comparing projects in existing markets and new markets. Further, these operations have to be balanced with complementary R&D activities, training and familiarization with new Rules and Regulations, and the development of next-generation ship designs, to be used as a basis for future projects.

2.4.2. Ship design - the process

Traditionally, ship design practitioners have carried out ship design as an iterative process consisting of several stages: concept design, basic design and detail design. This process was described in 1959 as a *design spiral* (Evans, 1959). The iterative nature of the process is a quality of complex man-made systems which involve many interconnected tasks carried out by different stakeholders, each with their own specialization area (Braha and Bar-Yam, 2007). Iterations are driven by the availability of new, or corrected information. Hence, the design process will keep iterating until the process has converged into a specific design specification or the expectations are fulfilled (Braha and Bar-Yam, 2007) or satisficing.

Although the goal of the design spiral was "to enable ship design problems to be solved most efficiently" (Evans, 1959, p. 672), the repetition of activities may compromise the effectiveness and efficiency of the process. Braha and Bar-Yam (2007) suggest that repetition represents around one-third (1/3) of the overall design time. Lyon and Mistree (1985) argue that the design spiral proposed by Evans may be an effective approach in those circumstances where ship design is not influenced by market competition. Hence, projects where ship designer and customer have almost unlimited time and resources for the project, so they can explore the problem and search for effective vessel design. This is, however, not the case of most of the ship design activities, strongly driven by market competition (Brett *et al.*, 2018). Based on the limitations of the design spiral, Andrews (1981) proposed a third dimension to the sequential ship design problem, to cope for the dynamism and open nature of the problem. Ship design practitioners have recognised the challenge such an iterative approach represents, and proposed, consequently, alternative views of the ship design process.

Benford (1965), Buxton (1972) and Erichsen (1989) claimed the importance of looking at the ship design problem from an economic perspective, especially at the earlier stages. Ships, after all, are investments, and ship owners purchase them expecting a future economic benefit. Building on the holistic nature of the ship design problem claimed in works like the ones of Mistree *et al*. (1990) and Brett *et al.* (2006), Mistree *et al*. (1990) propose a design paradigm integrating the concurrent systemic design approach complemented with a system engineering framework, termed *Decision-Based Design*. A major shift from the traditional ship design spiral of Evans was the fact of looking at the ship design problem as concurrent, rather than iterative. The goal of approaching the problem as concurrent is the reduction of the overall development time. Rather than refining the final vessel design by iterative, sequential learning; design activities were carried in parallel, by interconnecting them. Yet, as argued by Smith and Eppinger (1998), concurrent tasking may sometimes increase the total amount of rework, since data, information or knowledge gained during the design process may lead to repeat calculations, thereby increasing engineering effort; and potentially development costs and lead time. In ship design, many tasks are interconnected, for example, stability calculations depend on the definition of hydrodynamic characteristics, as well as on the estimation of weights and gravity centres. Such interdependency challenges the applicability of concurrent engineering in some stages of the ship design process. The use of a systems approach relying on a concurrent process, as opposed to an iterative process, requires a change of perspective (Mistree *et al.*, 1990).

The development of computer power brought to the ship practitioners new ways to approach the ship design problem. The man-machine iteration could give the designer more time to focus on the problem formulation (creativity), while the computer could take the role of iterate towards a final design solution, with critical review by the designer (Pawling and Andrews, 2011). The development has however guided designers towards the improvement of efficiency by means of time reduction (Lyon & Mistree, 1985). By looking at a reference publication such as *Transactions of the Royal Institution of Naval Architects* between 1960 and 2008 (Kreuzer, 2009), it is found that most of the development in ship design literature has been focused on specific mathematical and analytical principles to improve the precision of naval architecture principles. Rather than focusing on making the design process quicker, the availability of computational power has been directed towards the improvement of reliability (computerized-fluid-dynamics - CFD, finite element methods - FEM, detailed 3 dimensions modelling, etc), which, contrary to expected, has turned to increase the resources required.

Hence, although computers were introduced in designer's daily activities as a tool to accelerate the design process (the designer could get quicker answers to design decisions), little results show so (Cross, 2018a). It has however shown some negative effects on designers, such as inducing stress (Cross, 2018a). Computer-Aided Design (CAD) systems might lead to better communication among designers (Cross, 2018a), but also towards customers, especially by the use of 3D models or virtual reality (VR). Fallman (2003) sees sketching as a way for designers to express their ideas and communicate them to the rest of the stakeholders during the design process. Internalized in the computer-based design, prototyping is typified as a formal dialogue in design work (Fallman, 2003; Pawling and Andrews, 2011). The ship design industry has been using the most virtual prototyping in the maritime industry (Keane *et al.*, 2017). But sketching is more than a communication tool. Pawling and Andrews (2011) suggest that sketching is an important part of the internalization of the problem, as a tool to reinterpret ideas and incentive new ones. Thus, sketching techniques could be further exploited in ship design processes to accelerate the definition of the conceptual design as a tool to communicate with the customer and define their expectations. Today this communication is done based on the general arrangement (GA) of the vessel, which is substantially more time and resource consuming.

In some cases, the development of computer power has been used towards the acceleration of the conceptual design process. One example is VISTA (Virtual Sea Trials), where hydrodynamic, power production and auxiliary systems are integrated into a common simulation platform (Erikstad *et al.*, 2015). A similar example is Ulstein's toolbox, where commercial, operational and technical aspects of the vessel are integrated into one common tool (Keane *et al.*, 2017; Brett *et al.*, 2018). Thus, the naval architect has control over the entire conceptual design development. These tools pursue the objective of fast-track concept design, by giving quick feedback to designers on their decisions. One turn to the design spiral can be carried out in minutes, which gives the designer the ability to explore substantially more alternative designs. These newer approaches to ship design show a trend towards integrating the vessel design process in a broader business case, what Brett *et al.* (2018) name *business-centric ship design*.

These capabilities give the ability, and responsibility, to ship designer for moving upstream in the development of a vessel newbuilding project. This development has been spurred by the fact that problem definition plays a critical role in the effectiveness of the design process (Lyles, 1981; Suh, 1990). In ship design, problem definition can be related to the description of vessel's requirements (or resulting from initial customer expectations), which are typically presented to the designer as a written document, with a variety of precision and abstraction levels. Historically this aspect has been poorly handled by ship designers, and the definition of the requirements of the vessel has been left in its totally to ship owners. Karl F. Staubo, managing director at Clarksons Platou suggested in an interview, that one of the key factors when designing and building a vessel is its financing (Nordhaug and Hammer, 2018). The capabilities of the vessel, its newbuilding price, and the gearing (debt level) should be matched with the revenue-making potential of the vessel. For example, a vessel operating in the spot market, because of its volatility in incomes, get typically, lower loan to value than vessel operating under more stable contracts. Thus, a good technical design that does not reflect the commercial and operational characteristics of the market may not be built and, therefore, will not generate business for the ship design firm.

For this reason, modern ship design practices go beyond the traditional ship design activities like school book naval architecture and marine engineering and involve further in the vessel business case development. They provide market and technology insights and technical competence in the definition of the final requirements for the vessel design solution. This was already claimed by Erichsen (1989, p. 7), who suggested that "The user's requirements should be worked out in conjunction with the designers". In this way, unrealistic vessel requirements are identified, discussed and disregarded, and the conceptual ship design starts on the right set of requirements the first time. Figure 2-23 represents the typical activities carried out in a *traditional* ship design process and in a *modern (or novel)* ship design process.

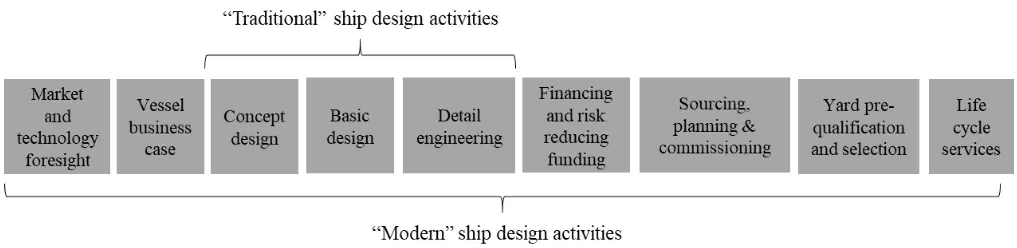


Figure 2-23 Activities of a traditional and a modern ship design process.

Figure 2-23 also reflects the movement towards downstream activities, including financing and risk-reducing funding support, sourcing and planning, yard qualification and life cycle services; activities traditionally done by suppliers.

2.4.3. Uncertainties in vessel design and operation

Handling uncertainty is an important part of today's shipping industry, from the design phase through the construction and the operation of the vessel; being the latter, where most of the literature has been focusing (Erikstad and Rehn, 2015). In regards to ship design, uncertainty appears in technical, commercial and operational aspects (Garcia *et al.*, 2016), influencing the development of new vessel design solutions (Wynn, Grebici and Clarkson, 2011). One example is uncertainty relating to the reliability and performance of innovative vessel designs or features onboard the vessels, which can often create an important dissuasive factor (Petetin, Bertoluci and Bocquet, 2011). For this reason, many shipowners prefer proven solutions for their new vessels to reduce intrinsic uncertainties in the ship design process. In spite of this, at the end of the day, each vessel is somewhat different from their predecessors and the benefits of standardization in the reduction of uncertainty are, as consequence, not being fully exploited.

Uncertainty plays a critical role when evaluating the goodness of a design (Gaspar, Hagen and Erikstad, 2016), both regarding how the vessel fulfils customer's expectations but also to how the vessel performs at a fleet level. The importance of this topic to the industry and academia is reflected in the rise of publications relating to this topic. On a search in *Scopus*, we find that the number of annual publications has raised from barely one or two per year during the 90s to more than 15 during the 2010s. Our search includes only articles written in English and published in journals or conference proceedings including "ship design" or "vessel design" and "uncertainty" or "uncertain" in their abstracts. A total of 214 publication were identified between January 1976 and July 2019 (*Scopus*, 2019). The historical distribution of publications is presented in Figure 2-24.

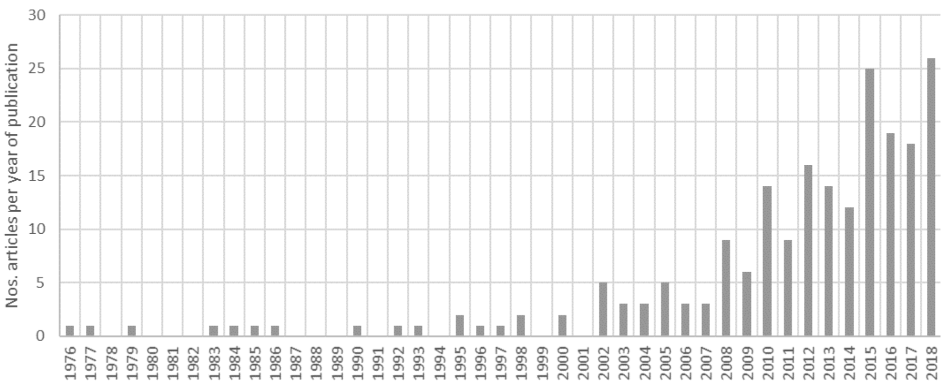


Figure 2-24 Historical distribution of scientific articles on ship design under uncertainty. Data from (*Scopus*, 2019).

A similar development of articles on the topic has been experienced for the publications on the last five editions of the *International Marine Design Conference* (IMDC), 9th, 10th, 11th, 12th and 13th edition respectively. Among the publications presented in Ann Harbor in 2006, only one paper related to uncertainty, more specifically to ship design in fuzzy environments. The 10th edition taking place in Trondheim had two papers on robust ship design, and the following edition in Glasgow had a total of seven articles, principally on the design of vessels for future potential scenarios. The last to conferences, in Tokyo and Helsinki respectively had nine articles each with special focus on ship design under uncertainty.

This literature on ship design under uncertainty covers topics in several aspects of the design, construction and operation of ships, which can be categorized in technical, operational and commercial perspectives. Technical aspects, such as the hydrodynamic optimization of the vessel (Campana *et al.*, 2015), the selection of the installed power (Vrijdag and de Vos, 2010) or the prediction of the bollard pull (Vrijdag, de Jong and van Nuland, 2013). An example of operational uncertainty is the evaluation of the sea ice conditions in the design of a platform supply vessel by Choi, Erikstad and Ehlers (2015). The commercial operation of the vessel plays an important role in the design phase and, therefore, has been studied accordingly. Plessas and Papanikolaou (2015) studied the design optimization of a bulk carrier considering the uncertainty of fuel prices during the vessel's lifecycle. Similarly, Puisa (2015b) studied the effect of fuel prices and passenger and cargo demand in the design of a Ropax vessel and Hiekata *et al*. (2015) propose a method to maximize operational value considering the variability of vessel's propulsion performance and fuel prices. Finally, Pettersen *et al*. (2018) integrate the three aspects, technical, operational and commercial uncertainties in the design of a large offshore construction vessel. Uncertainty related to the operational performance of vessels can have a domino effect on the performance of the activities it is involved with. One example is offshore windfarms, where it is recognised that uncertainty from offshore installations can have a substantial negative effect on scheduling and capital costs (CAPEX) (Paterson *et al.*, 2018).

There is also uncertainty surrounding the construction phase. When facing a (design) problem, Waldron (1992) suggests that the knowledge base is governed by the problem itself and does not depend on the designer. This assumption implies that the designer may be faced with unfamiliar information and he or she has to make decisions based on partial information. On a strategic perspective, the selection of a building strategy will influence the delivery time, production quality and the overall construction cost. Hence, the selection of an offshoring strategy (Semini *et al.*, 2017) or the establishment of an advanced outfitting approach (Lamb, 2004), should be considered accordingly. Another example of uncertainty during the construction phase is the measurement of the gravity centre during the inclining experiment as described by Woodward *et al*. (2016).

The operational phase is the one which has been given more attention since there are many uncertainty factors which may cause delays and influence the performance of the vessel and its cost of service (Nowacki, 2010). The variability of contextual factors and ship performance over time requite adaptive operations (Rehn *et al.*, 2019), both involving changeable designs and operational strategies. Thanopoulou and Strandenes (2017) evaluate the historical effect of long-term uncertainty in shipping performance, recommending a focus on resilience as a prerequisite for market survival. Following this principle, Pettersen and Asbjørnslett (2016) study the benefits of the design of a resilient fleet for emergency response operations. Murphy (2018) suggest that market volatility is correlated with market consolidation in the container shipping industry. He argues that such volatility is the consequence of container carriers' focus on market shares, reflected in freight rates and overall competitiveness and not so much the ship technical aspects.

The commercial perspective has been advocated by Benford (1965), Buxton (1972) and Erichsen (1989), and since then, commonly considered in ship design processes. However, in most cases only as a simple cost calculation at the end of each design iteration, rather than as a reference for critical trade-off decisions (Veenstra and Ludema, 2006). Vessel cost should not be the only commercial factor considered during the design process, although it has a primary role. Vessel price should be correlated, among others, with the capacity of the owner to finance the new building program and the revenue-making capability of the vessel. It is for this reason why both, cost and revenue capability should be used to balance the final vessel design (Brett *et al.*, 2018). The relationship between design specification and revenue making is fairly direct (Veenstra and Ludema, 2006), hence, the maximum price that the shipowner could afford to achieve an effective vessel. This is less clear in markets like the one for offshore vessels (Dahle and Kvalsvik, 2016). Stability and predictability are highlighted as the most important factors considered by shipping companies when planning to establish new operations (NSA, 2018).

Fuel prices represent a critical uncertainty for ship owners and operators. Historically, the volatility of fuel prices has brought both threats and opportunities for industry players. Yet it has been demonstrated that the perfect prediction of fuel prices for the entire lifecycle of the vessel is unrealistic. One way of handling this uncertainty is reducing the dependency of profitability in operations with respect to fuel prices. This has been a very attractive strategy among shipping companies since it reduces the downsides of increasing fuel prices but also increases the upsides of lower fuel prices. Hence, ship designers have focused on improving the propulsion efficiency of the vessels by means of slimmer hull lines, bulbous bows or newer propeller designs. On the other hand, these improvements incentivized the rise of vessel speeds (the consumption of a vessel sailing at 25 knots was equivalent to an older vessel sailing at 23 knots), at a time of lower fuel prices. Yet, the posterior rise of fuel prices demonstrated that although vessels were theoretically more efficient hydrodynamically, in practice, they were as bad as before when reducing their speeds, resulting in many retrofits of bulbous bows and propellers (Kalgora and Christian, 2016), when they had to sail slower. The learning from this experience was that vessels should be more flexible with regards to vessel speed, leading towards different, less draft-dependent bow shapes, of which some examples are the X-Bow from Ulstein or Axe Bow from Damen, flexible bulbous bows (Watle, 2017) and lower vessel speeds in general (Wiesmann, 2010). Another traditional strategy to handle fuel price uncertainty in shipping has been the purchase of large amounts of fuel when prices are low (Tuttle, 2016) or long-term agreements at relatively fixed prices combined with currency hedging.

A similar challenge presents the uncertainty regarding vessel demand. Alliances, are typical in sectors like container shipping to both, reduce operating costs and to strategically deal with future demand uncertainty (Niamié and Germain, 2014). Long-term contracts are a way of ensuring tonnage availability for cargo owners and tonnage utilization for vessel owners. Contracts of Affreightment (CoA) are agreements between a shipowner or operator and a cargo owner to transport a fixed amount of cargo within a given period of time. In most of these contracts, the vessel owner has the flexibility to use almost any of the vessels in his or her fleet to transport the cargo. This contract ensures that the cargo owner retains the availability of tonnage without requiring the full year charter of the vessel. For the shipowner or operator, it represents work for the vessels and gives flexibility with regards to what vessel to use, where and when.

The combination of technical, commercial and operational uncertainties is very apparent in the conceptual design phase. Ship designers should guide ship owners and operators in the very early stages and improve, therefore, the effectiveness of the design decision-making process. An example of how a ship designer can support shipowners in this process is Ulstein's luxury categorization for exploration-cruise vessels (Garcia, Brett and Ytrebø, 2018). Figure 2-25 represents the positioning of the vessel in the market, and therefore indicating the newbuilding price level for the vessel (and associated vessel size, interior finishing, functionality), as well as the potential revenue per passenger. In this graph, each vessel is represented by its *service ratio* (Crew/pax) and its *space ratio* (GT/pax). The size of each symbol in Figure 2-25 represents the capacity of the vessel in terms of the number of passengers. Such graphical representation helps designers and ship owners to identify the expectations and requirements of the vessel based on the market demands the cruise operators want to cover. Wainer (2009) recommends graphical representations as a way of reducing uncertainty and better communication and information sharing.

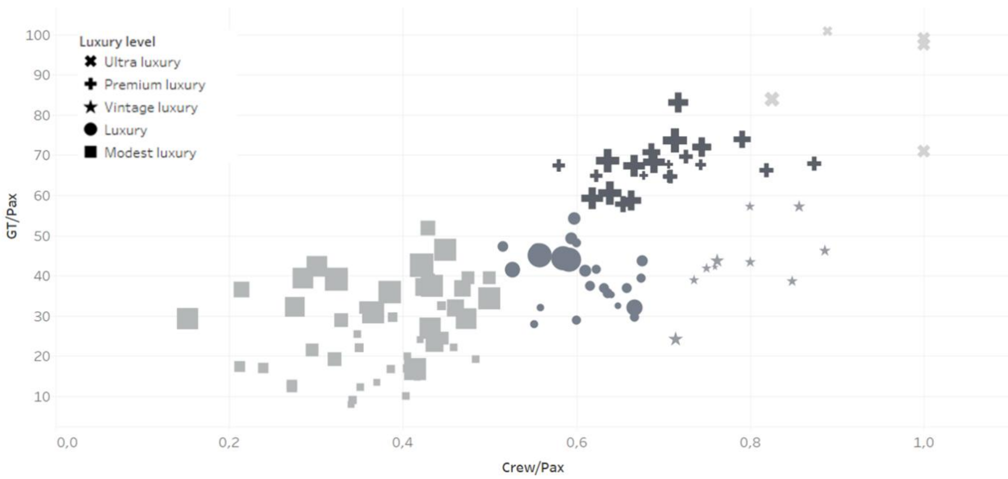


Figure 2-25 Luxury categorization of small-sized cruise vessels.

Some shipping companies state explicitly the set of risks and uncertainties that affect their operations. TechnipFMC claims that "these are important factors that could cause the Company's actual results" (Pferdehirt, 2019, p. 38). It is the responsibility of the companies to "identify key risks at an early stage and develop actions to measure, monitor and mitigate their likelihood and impact". "Effective risk [and uncertainty] management is fundamental to the Group's performance and creates sustainable value for our stakeholders (Cahuzac, 2019, p. 18). An example of uncertainty factors explicitly stated by an offshore oil & gas contractor in its annual report is included in Table 2-9. Most of these factors have been identified also in our literature review work and are included in our investigative model.

Table 2-9 Risk and uncertainty factors for an OO&G contractor (Pferdehirt, 2019).

Vessel delivery	Market competition	IT failure (cyber attacks)
Piracy	Rules & regulation	Technolgy development
Vessel demand	Service demand	Seasonal developments
Debt rating	Currency exchange	Suppliers and subcontractors
Tax regulations	Political disruptions	Weather conditions

2.5. Frameworks for system design under uncertainty

The multidisciplinary characteristic of marine system design requires involving multi-field expertise teams (Kusiak and Wang, 1994). The ship designer has to gather information and data from multiple sources, interpret it and integrate it into the final vessel design. In many cases, due to the nature of the problem, little information needs to be gathered, as a ship designer's tacit knowledge[5] may suffice to develop an effective vessel design. For example, the design of a Panama-size[6] bulk carrier. The structure of the market and the vessel design represent, in this case, a well-structured problem (Pettersen *et al.*, 2018). Such a problem will not require an intense exploration phase and rather should focus on the exploitation of existing knowledge. Other ship segments, however, are characterized as wicked or ill-structured, since the definition of the vessel requirements is not a straightforward task. Naval vessels, yachts or offshore vessels require a more thorough evaluation of the vessel business idea as a premise to develop an effective vessel design solution. This is what Andrews (2011) names requirements elucidation, a way to attack the wicked-problem and determine "what is really wanted …, and what can be afforded".

As part of this research work, I have explored the applicability of two approaches to handle the complexity and uncertainty surrounding the ship design process: Accelerated Business Development approach (ABD) and Responsive Systems Comparison method (RSC). Both methods are described in more detailed in the paragraphs below. The ABD is a methodology used by Ulstein since 2007 and to which I have had access and exposure since 2014, participating in more than 10 concept design developments following this procedure. This vessel concept design approach was developed as part of a European Union research project over 4 years (Brett, Boulougouris, *et al.*, 2006; Brett, Carneiro, *et al.*, 2006). The RSC methodology was developed by the systems engineering advanced research initiative (SEAri) at the *Massachusetts Institute of Technology* in 2008. I was exposed to this methodology in 2016 and 2017, including three short research stays at SEAri, which involved a deep study of the methodology and the application to a case study. The results were published by Pettersen *et al.* (2018).

5 Knowledge that emerges from experience.

6 Referring to vessels that fulfil the size limitations of the Panama Canal.

2.5.1. Accelerated Business Development (ABD)

The *Ulstein Accelerated Business Development* (ABD) is an approach that structures the process of turning a vessel business idea into a comprehensive business concept and ship specification (Brett, Boulougouris, *et al.*, 2006). The Ulstein ABD was initially developed to handle the intrinsic complexity and uncertainty of ship design (the wicked problem), by supporting the early design process with fast, fact-based decision making (Ulstein and Brett, 2015). It provides guidance and decision-making support to the ship designer, investors, ship owners and other relevant stakeholders in the development of new vessel designs (Brett, Carneiro, *et al.*, 2006), especially in those cases characterized as wicked or ill-structured problems. The most relevant information affecting the vessel business case is elicited in a compressed series of workshops which are used as bases to conceptualize the vessel design, to further develop the basic and detail designs. Notice that during an ABD process, the intention is not to gather information to carry out in-depth analyses, but rather, to explore in-breath potential factors affecting the business case and vessel design and facilitate a continual real-time decision-making process. Hence, the ABD driver (the person structuring and facilitating the workshops and activities), needs a reference to evaluate continually whether a set of information or analysis is good enough, or more in detail evaluations are required. Here is where the notion of value of information comes into place. Its nine modules can be divided into exploration and exploitation activities respectively, as shown in Figure 2-26.

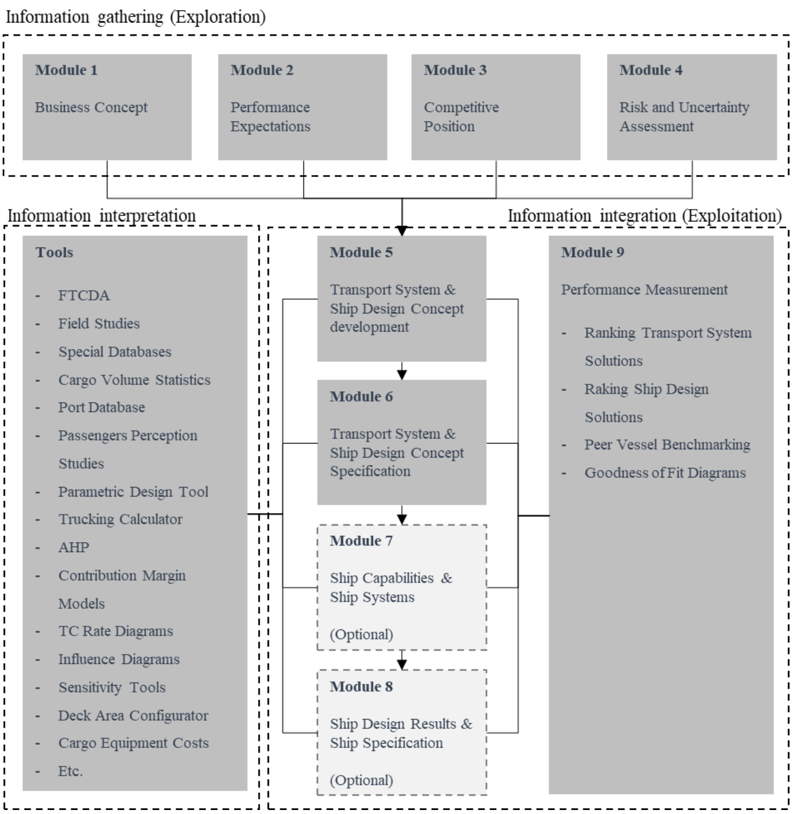


Figure 2-26 Accelerated Business Development (ABD) modules (adapted from (Brett *et al.*, 2018)*).*

The nine modules conforming the Ulstein ABD are developed in a way that forces the users to think about all the aspects of the business concept which influence the vessel design and to explore areas that otherwise wouldn't be considered (Brett, Boulougouris, *et al.*, 2006). Its structure and the multi-disciplinarily character of the participants spur the exchange of information among them, facilitating learning and better decision-making (Surowiecki, 2005). A more detailed description of the activities taking place in the different modules can be found at (Brett, Boulougouris, *et al.*, 2006), or more recently in (Keane *et al.*, 2017; Brett *et al.*, 2018).

Modules 1 to 4 (see Figure 2-26) relate to the business concept development, to test the initial expectations of the customers or stakeholders being involved (shipowner, operator or charterer) and define vessel requirements and constraints. The modules are developed in a way that forces the users to think about all the aspects of the business concept which influence the vessel design, and to explore areas that otherwise wouldn't be considered (Brett *et al.*, 2006). Modules 5 to 9 (see Figure 2-26) relate to the vessel concept development and the definition of a vessel design specification fulfilling the design requirements elicited in modules 1 to 4. The series of complementary analyses tools facilitate the interpretation of the information gathered during the exploration phase and support the design decisions taken during the vessel concept development phase. In the paragraphs below, three of these tools are described in more detail, relating their role in the handling of uncertainty in the design process: (i) daily vessel economics, (ii) peer-vessel benchmarking, and (iii) goodness-of-fit metrics. Daily vessel economics refers to the cost and revenue associated with a vessel design solution on a per-day equivalent level, including the uncertainty factors associated with them. These vessel expenses can be a trade-off with the potential vessel daily revenue and extract a contribution margin or return on investment (ROI) benchmark. Peer-vessel benchmarking builds on the methodology presented by Ebrahimi *et al*. (2015) and supports the selection of a better vessel. The three measures support and contribute to the reduction of uncertainty towards the vessel owner: Will I make money with this vessel? How does it look compared to my current vessels? And compared to competitors? How well does it satisfy my expectations? and can it be used by the ABD facilitator and ship designer to evaluate when a set of information and analysis is good enough and decide to finalize the exploration phase to initiate the detailing of the vessel and further verification during the exploitation phase.

Vessel economics: vessel costs, relating to capital expenditure (CAPEX), operational expenditures (OPEX) and voyage expenditures (VOYEX) are calculated following the model proposed by Stopford (2009); although includes some modifications to be adapted to the peculiarities of the different vessel segments and ship types and the evolution of costs over time. The revenue of the different vessel design solutions is associated with the rates of their relating vessel segments or to the associated revenue-making capability of the vessel measured against peers. For a platform supply vessel, for example, rates are market-driven, while for a cruise vessel it comes defined by how many passengers it is carrying and how much are they willing to pay per night onboard. To count for the uncertainty relating to revenue making, in addition to the current dayrates, 10 years average, 3 worst years average and 3 best years average are included to reflect the dynamism of the market. A similar exercise can be carried out with fuel prices or crew costs, to see the influence of those in the overall business case.

Vessel performance benchmarking: Ulstein's vessel performance benchmarking is used to compare the technical, operational and commercial performance of vessels inside each specific vessel segment (Ebrahimi, Brett, Garcia, *et al.*, 2015). The objective of such benchmarking methodology is to say factually, which is a better vessel design solution among peers (Ulstein and Brett, 2015). Furthermore, it can be used as a reference of the designer and the vessel owner to decide what is good enough and stop the exploration phase and focus on further developing and verifying the concept design.

Goodness-of-fit (GoF) index: the GoF index evaluates a vessel design towards the fulfilment of its intended expectations set by relevant stakeholders. It ranks the different concept design alternatives under evaluation and gives, on a quantitative way, to ship designer and vessel owner an idea of what vessel concept is closer to their expectations.

One recent example of the application of ABD in ship design can be found in Garcia *et al.* (2018).

2.5.2. Responsive Systems Comparison Method

The Responsive Systems Comparison (RSC) is a structured method for supporting decision-making in complex design problems in uncertain environments. The RSC method was originally presented in Ross *et al*. (2009) and Ross, McManus, e*t al.* (2008), but evolved to its current form in later papers, a recent reference being Schaffner, Ross, & Rhodes (2014). RSC is built on the strengths of *Tradespace Exploration* (systematic examination of a wide variety of solutions), *Value-based Decision Theory* (evaluation of solutions in terms of utilities) and *Epoch-Era Analysis* (organizing, and quantifying changing context, needs and systems) (Ross *et al.*, 2008). The method consists of nine process elements grouped in three main activities as reflected in Figure 2-27: (i) information gathering, (ii) alternatives evaluation and (iii) alternatives analysis.

Processes 1 to 3 represents the information gathering phase. Process 1, value-driving context definition, consists of the definition of the business proposition of the design problem at and. In this step, each of the stakeholders defines its value proposition with regards to the new design. This value proposition is transformed into a value function in process 2, value-driven design formulation. The different value attributes are derived from the value proposition defined in process 1. Finally, process 3 explores the better understanding of the operating environment and the exogenous uncertainties affecting it. In this step, and before proceeding to the definition and evaluation of alternative, the designer and RSC participants define a set of alternative operating contexts (named Epochs).

Process 4, the design-epoch tradespaces evaluation, is where the different design alternatives are elicited. In this process, the designer defines a set of design alternatives and models the mapping between the value space and the design space. Thus, each design alternative is defined by a utility measure, multi-attribute utility (MAU), and a cost measure, multi-attribute expense (MAE).

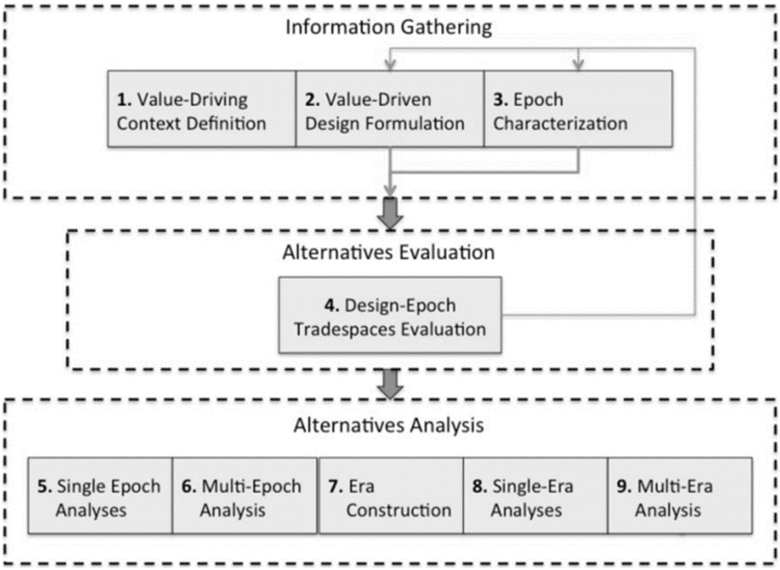


Figure 2-27 Responsive System Comparison (RSC) method (Schaffner, Ross and Rhodes, 2014).

The final stage, alternatives analysis, consists of five processes, processes 5 to 9. The first of these processes, single epoch analyses, consist of the static evaluation of design alternatives. Hence, the design alternatives are evaluated in isolated Epochs. Design alternatives are evaluated on a tradespace and those closer to the Pareto front are preferred. The tradespace consist of the transposition of MAU and MAE. Hence, design alternatives with the highest utility and lowest cost are preferred. The second process, multi-epoch analysis, evaluates the robustness of the vessel designs. Hence, the designer explores how alternative designs perform in a set of predefined Epoch. Designs with the higher performance overall are preferred Yet, is unrealistic to consider that the operating context will not change over the design's lifecycle (single epoch) or that all potential futures can happen (multi-epoch). Eras are descriptions of the development of the future that combines in a pre-defined order, the changes in operating context. This is the objective of process 7, to define alternative future developments (Eras). In process 8, the different design alternatives are evaluated over a given Era. The process is similar to that of process 6, but in this case, the set of Epoch is limited to those present in an Era. In this situation, the designer can explore flexible value robust designs, by considering design changes to adapt the design to the different Epochs contained in one Era. The final process, multi-era analysis, which expands the study of value robustness over to alternative futures.

A recent example of the application of RSC in ship design can be found in Pettersen *et al.* (2018).

3. Theorization

Development of theory is a central activity in both uncertainty management and decision-making under uncertainty. In Chapter 2 of this thesis, we have explored the state-of-the-art literature in these research areas. Unfortunately, with regards to uncertainty, there is no unanimity regarding what theory is more representative or recommended (Miller, 1993), either to measure *actual* or *perceived* uncertainty. Furthermore, none of the existing models in the literature reviewed seems to cover the peculiarities of uncertainty in ship design processes the way it is normally executed and experienced. Yet, it is considered critical to this research work to be able to measure uncertainty in one way or the other. Hence, it was necessary to develop a revised research model for this specific research problem and apply a multi-perspective theoretical approach to try to explain the relationships and causality of uncertainty and decision-making effectiveness in conceptual ship design. Our research model builds on the findings of other researchers in this area, like Downey and Slocum (1975), Miller (1993), Elbanna and Gherib (2012) and Ramasesh and Browning (2014) and connects them with the uncertainty factors extracted from ship design literature, including Gates (1984), Ulstein and Brett (2012), Vrijdag, Stepersma and Grunditx (2012), Andrews and Erikstad (2015), Gaspar *et al*. (2015) and Puisa (2015b).

3.1. Classification of uncertainty

Different uncertainties require a different strategy for how to handle them. Courtney *et al*. (1997) and Thissen and Agusdinata (2008) recommend selecting the uncertainty handling strategy based on the *level* of uncertainty. Tversky and Kahneman (1992) name it degree. Walker *et al*. (2003) extend the evaluation beyond the level, considering additionally *location* and *nature* as relevant factors to consider when categorizing uncertainty. The nature of uncertainty is also considered by Wynn, Grebici, and Clarkson (2011). Similarly, Haberfellner and de Weck (2005) and Brashers (2001) suggest considering the *time* dimension of uncertainty. This section includes a literature review on the classification of uncertainty by: (1) source, (2) nature, (3) time, (4) level and (5) location. This classification of uncertainty will be used later in this thesis to reflect what strategies are recommended to each class or type of uncertainty.

3.1.1. Uncertainty sources

In a broader perspective, *agent* behaviour and *contextual* factors, are described as the principal sources of uncertainty (Fantino and Stolarz-Fantino, 2005; Kochenderfer, 2015). Wernerfelt and Karnani (1987), with a focus on business development, expand this classification to four sources: demand structure, supply structure, competitors, and externalities. In relation to project management, Saunders, Gale, and Sherry (2013b) identify five sources of uncertainty in their literature review: complexity, information load, turbulence, external factors and relationships between parties; sources which are grouped, at the same time, in three determinants: culture, context and capability.

In product development, Fox *et al*. (1998) classify the uncertainties in market, technology, and process. Following a similar reasoning, Perminova (2011) suggests, relating to project management, four types of uncertainties: technical, contract, management /organizational and customer. Similarly, but in service development, O'Connor and Rice (2013) and more recently Ramirez Hernandez, Kreye and Pigosso (2019) identify technical, environmental, organizational and resource uncertainty.

For ship design and operation, Erikstad and Rehn (2015) propose four types of uncertainties in marine system design: economic, technology, regulatory and physical. Gaspar, Hagen, and Erikstad (2016) inspired by the classification proposed by Rhode and Ross (2010) on complexity aspects propose a categorization of five aspects of uncertainty in system design: structural, behavioural, contextual, temporal and perceptual. Liwång (2015), considers four sources of uncertainty, the three suggested by Abrahamsson (2002) parameter, model and completeness, and one additional named input uncertainty. Those four, contributing to the uncertainty in the output. Salaken *et al.* (2017) have similar findings, identifying a correlation between input and output uncertainties (large input uncertainty = large output uncertainty). Coleman and Steele Jr. (2009) propose three groups of uncertainties relating to engineering problems, input, methods and model uncertainty. Burger (2017) builds on the grouping proposed by Coleman and Steele Jr. to classify the resources of uncertainty and their magnitudes, relating to the predictions of vessel speed and fuel consumption of heavy lift vessels. Ramasesh and Browning (2014) identify four factors contributing to the generation of uncertainty, viz. complexity and complicatedness, relating to project design issues, and mindlessness and project pathologies relating to behavioural issues.

The different types of uncertainties suggested by the different authors in the literature reviewed are, in most of the cases, correlated; in other words, uncertainties tend to reinforce each other (Gaspar, Hagen and Erikstad, 2016). Kreye (2017) names it "knock-on effects", to uncertainties causing other uncertainties. However, although many uncertainties affect each other, not all do overlap (de Weck, Eckert and Clarkson, 2007). This concept is exemplified by the representation of uncertainties in layers as proposed by Miller and Lessard (2001). From the inner-most layer consisting of technical and project uncertainties to the outer-most including natural uncertainties. Each layer will interact with the neighbour layers, influencing and being influenced by them.

A comparison of the classification of uncertainties proposed by some of the authors reviewed above is presented in Table 3-1. Although the types of uncertainty identified by the different authors in the literature reviewed do not represent one-to-one those of other authors, we have tried to relate them by their proximity.

Table 3-1 Overview of alternative classifications of uncertainties proposed by different authors.

Research field	Type of uncertainty					Source
Decision making	Context or environment	Agent or decision-maker				(Fantino and Stolarz-Fantino, 2005)
	Environment	Agent behaviour				(Kochenderfer, 2015)
Business	Demand structure; supply structure; externalities	Competitors				(Wernerfelt and Karnani, 1987)
Project management	Turbulence; external factors	Relationships between parties	Complexity; information load			(Saunders, Gale and Sherry, 2013b)
		Project parties	Estimations		Stages of the project	(Johansen *et al.*, 2014)
		Customer	Technical	Contract	Management; organizational	(Perminova, 2011)
Systems engineering	Context	Perception				(Boschetti, 2011)
	Context		Model	Input		(Walker *et al.*, 2003)
	Environment; context		System			(McManus and Hastings, 2005)
			Model	Input	Methods	(Coleman and Steele Jr., 2009)
Product & service development	Market		Technical		Process	(Fox *et al.*, 1998)
	Environmental	Resource; relational	Technical	Environmental	Organizational	(Ramirez Hernandez, Kreye and Pigosso, 2019)
Ship design		Regulatory	Physical, technology, economic			(Erikstad and Rehn, 2015)
	Contextual; temporal	Perceptual	Structural; behavioural			(Gaspar, Hagen and Erikstad, 2016)
			Model, parameter	Input, completeness		(Liwång, 2015)

3.1.2. Uncertainty nature

With regards to the nature of the uncertainties, most of the literature reviewed groups uncertainty in *endogenous* and *exogenous*, as well as a combination of those two named *hybrid* (Lin *et al.*, 2013). Similarly, other researchers denominate them, respectively, epistemic and variability or ontic uncertainties (Walker *et al.*, 2003; Derbyshire and Giovannetti, 2016). Endogenous or epistemic[7] uncertainty refers to the lack or inaccuracy of information, which can be actively influenced by the decision-maker. Exogenous or ontological uncertainty, on the

[7] From the Greek episteme, meaning *knowledge, understanding, scientific knowledge or skill* (Oxford, 2016).

other hand, refers to the factors that vary over space and time which are beyond the control of the decision-maker. Hybrid uncertainties combine both types.

Walker *et al*. (2003) distinguish three sources that may influence the presence of variability uncertainty, being: behavioural variability, societal variability, and natural randomness. Behavioural variability represents the irrational behaviour of stakeholders involved in the project or the decision-making process. Similarly, societal variability represents a macro-level of that irrational behaviour; considering here market changes such as demand and supply or market expectations. Natural randomness refers principally to unforeseen events such as disrupting technologies (Christensen, 2016) and Black Swans (Taleb, 2010). Similarly, Hastings and McManus (2005) classify epistemic or endogenous uncertainties into two groups: lack of knowledge and lack of definition. A similar distinction is proposed by Coleman and Steele Jr. (2009), who argue that uncertainty is generated rather by precision, bias errors, or a combination of both factors. A different categorization is proposed by Jacobs, van de Poel and Osseweijer (2014), who propose four factors named: lack of knowledge, ignorance, system complexity and ambiguity. Lack of knowledge is related to known unknowns, while ambiguity is related, by the authors, to unknown unknowns.

A parallel categorization is proposed by Veenman and Leroy (2016) who distinguish between cognitive uncertainty, related to the lack of knowledge, and normative uncertainty, related to the lack of clarity regarding the inputs. Further, Höllermann and Evers (2017) group uncertainties into two categories, viz. fundamental and procedural. The former includes those uncertainties relating to contextual factors, while procedural uncertainty relates to process and planning factors.

A broader classification of uncertainty, this time relating to the design of complex systems, is proposed by Thunnissen (2003), who in addition to epistemic and aleatory (or alternatively referred as exogenous or variability), recognises ambiguity and interaction. Ambiguity is described by Thunnissen as the uncertainty resulting from poor communication, and therefore, it may be considered within the categorisation of epistemic or endogenous proposed from other authors. Similarly, interaction describes the uncertainty resulting from the interaction of multiple events and may be considered as part of exogenous uncertainties. Thunnissen (2003) makes a sub-categorization of epistemic uncertainty differentiating among model uncertainty (relating to errors), phenomenological (relating to the uncertainty resulting from the technique or process used), and behavioural uncertainty.

A comparison of the classification of uncertainties proposed by some of the authors reviewed above is presented in Table 3-2. Figure 3-1 summarizes the categorization of uncertainty by nature.

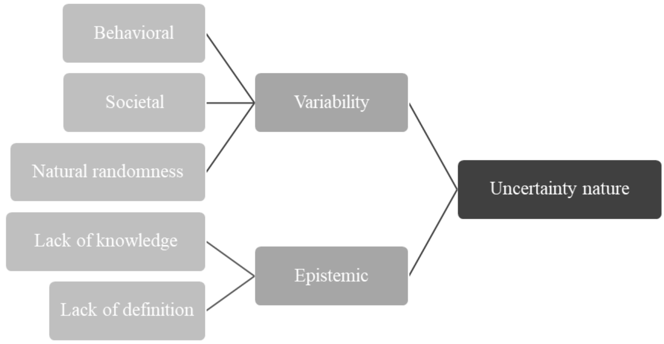


Figure 3-1 Proposed categorization of uncertainties by nature.

Table 3-2 Categorizations of uncertainty by nature.

Source	(Derbyshire and Giovannetti, 2016)	(Walker *et al.*, 2003)	(Lin *et al.*, 2013)
Research field	Product development	Systems engineering	
Type of uncertainty	Epistemic	Epistemic	Endogenous
	Ontic or ontological	Variability	Exogenous

3.1.3. The time dimension of uncertainty

The *phase* of the project, product development or design process in which the uncertainty arises, and the *extension* of the uncertainty over time are relevant parameters for the selection of a strategy for handling or managing uncertainty (Brashers, 2001; Haberfellner and de Weck, 2005). As the design process proceeds and following the production, it is common that the designer gains more knowledge about the product as features are defined and the product starts taking shape, hence uncertainty should decrease (Jacobs, Van De Poel and Osseweijer, 2014). As a reference, see the cone of uncertainty proposed in Figure 2-13. An example is the lightweight of a ship. In conceptual ship design, the lightweight is estimated based on the main dimensions of the vessel and shape ratios extracted from similar vessels. As the design is developed, more information becomes available, and lightweight can be calculated as the summary of the weight of individual elements. Finally, when built, the lightweight of the vessel is confirmed when the vessel is floating.

Considering the phase of the design process, Haberfellner and de Weck (2005) distinguish between uncertainties arising during the design phase and those during the life cycle of the product; which is equivalent to planning and execution phase in project management. In the shipbuilding industry, we would distinguish between those uncertainties arising during the design and construction phase from those during the operation of the vessel. On a time dimension, but from an extension perspective, Brashers (2001) distinguish between short-lived and ongoing uncertainties. Where the former are uncertainties with a relative short-life in the project. Jacobs, van de Poel and Osseweijer (2014) suggest that the degree of uncertainty faced on a design decision depends on the lifecycle of the artefact, and in the duration of its (potential) effects.

3.1.4. Level of uncertainty

The level of uncertainty measures, as its name indicates, the level of knowledge, more specifically, the lack of knowledge. The level of uncertainty ranges from an idealized complete determinism to absolute ignorance, beyond indeterminism. It shall be noticed that the literature found and reviewed in this research with regards to the level of uncertainty relates exclusively to the prediction of the environment (or contextual uncertainty). Walker *et al*. (2003) identify four levels, named: statistical uncertainty, scenario uncertainty, recognized ignorance and total ignorance. Similarly, and focusing on life cycle uncertainties, Courtney, Kirkland, and Viguerie (1997) define four equivalent levels: close enough future, alternative futures, a range of futures and true ambiguity. Before them, Emery (1967) had differentiated among four types of ideal environments viz., placid-randomized, placid-clustered, disturbed-reactive and turbulent fields. Emery reflected and suggested the type of behavioural response required in each of the four environments in order to survive, relating a different strategy to each of them. Scherpereel (2006) classifies decision problems into three categories relating to the level of uncertainty they involve. As such, he considers first-order problems, characterized by certainty and simplicity, second-order decisions, with probabilistic uncertainty and finally, third-order problems, with genuine uncertainty, complexity, and dynamics.

Figure 3-2 compiles a collection of categorizations of uncertainty levels ranging from complete determinism, known knowns (I know I know), to indeterminism, unknown unknowns or unconscious uncertainty (I don't know I don't know). In between those two states, there is a range of states of conscious uncertainty denominated known unknowns (I know I don't know). Further, Lindaas and Pettersen (2016) propose an additional state where "we don't know we know", named unknown knowns. The authors argue that unknown unknowns, outliers by nature may be predictable, contrary to Taleb's claim (Taleb, 2010). This argument is in line with Gladwell (2009), who claims against the total randomness being outliers. The author discusses reasons and provides arguments behind some cases of outliers in our human society.

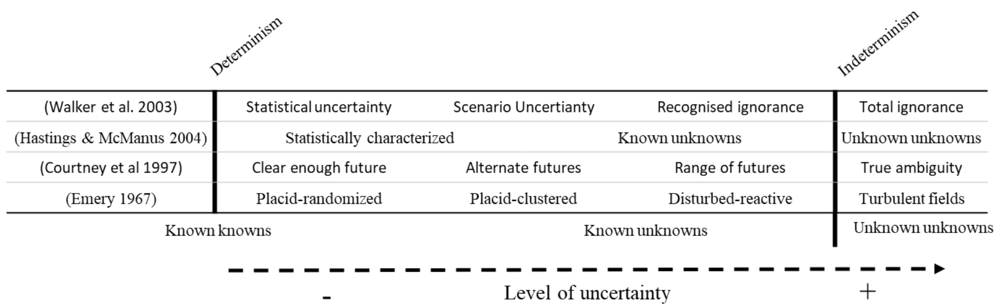


Figure 3-2 Categorizations of certainty levels.

Samset (1998) categorises the uncertainty level in projects from low to high. The level of uncertainty depends, according to Samset, on the type of project and the project context. Thus, larger and more complex projects will have consequently higher levels of uncertainty. The same consequence has the act of moving from developed countries to countries under development. The same effect was found by Ahir, Bloom and Furceri (2018), see Figure 2-14. Of the two factors suggested by Samset, project context has the strongest contribution to uncertainty (Samset, 1998). From a design perspective, Jacobs, van de Poel and Osseweijer (2014) argue that the level of uncertainty faced on a design decision depends on three parameters: design type (whether it is a radical design or conventional), the design phase (conceptual, basic or detailed), and the kind of artefact.

3.1.5. Categories of uncertainty

Milliken (1987) proposes three categories of uncertainty further developed by Boschetti (2011), Krishnan and Ramasamy (2011) and Regan (2012), viz. *state*, *effect*, and *response*. State uncertainty refers to the uncertainty perceived regarding the environment. The lack of clarity regarding the effect of uncertainty in the organization or project is defined as effect uncertainty. Response uncertainty refers to the lack of information regarding the alternatives to respond to uncertainty and the consequences of those.

3.2. *Uncertainty in ship design* – the independent variable

Miller's environmental uncertainty scale (Miller, 1993) is currently the principal reference, with a recent application on Ashill and Jobber (2010), Bradley (2012) and Elbanna and Gherib (2012). Miller's scale measures though 35 items the perceived environmental uncertainty in six areas viz. *government and policies*, *economy*, *resources and services*, *product market and demand*, *competition* and *technology* (Miller, 1993). Following a 7-point Likert scale, Miller classifies each of the 35 items in a ruler from predictable (1) to unpredictable (7). However, given the complexity of today's decision-making problems, representing the ship design decision-making process in the present research, it is not adequate to limit the examination to just environmental uncertainty (Elbanna and Gherib, 2012). Miller's scale focuses only on environmental uncertainty, utilizing industry and firm-specific variables, which represent the external factors to the firm. Another example is the work of Lawrence and Lorch (1967), who focus on uncertainty in inter-organizational factors. However, these are only partial evaluations of the uncertainty present in decision-making, and we haven't found any research on a complete evaluation of uncertainty that could be used to quantify uncertainty in conceptual ship design processes. This bias is perhaps what Taleb (2010) refers to as tunnelling, where researchers have focused only on well-defined sources of uncertainty.

Another alternative to measure perceived uncertainty is the work of Downey and Scolum (1975), who characterize uncertainty as a psychological state. The authors suggest four sources of variability in perceptual uncertainty, named: *perceived environment*, *individual cognitive processes*, *individual's experience*, and *social expectations*. The environment is characterized by Downey and Scolum (1975) by its complexity and dynamism, following Duncan's proposal (1972). The perception of complexity (number of interactions), and dynamism (variability of decision-making factors) show a positive relation to the perception of uncertainty. Further, the ability of the decision-maker to cope with ambiguity (individual cognitive processes), its experience in similar decision-making situations (behavioural response repertoire) and the trustfulness in the other stakeholders (social expectations) also have a positive relationship with perceived uncertainty (Downey and Slocum, 1975).

From a different perspective, Ramasesh and Browning (2014) propose a conceptual framework to capture the likelihood of finding uncertainty factors in product development, see Figure 3-15. Although the authors didn't quantify the strength of the proposed relationships, they argue the need for such exercise and suggest that this would benefit decision-makers on allocating efforts towards dealing with uncertainty. All four proposed factors (*complexity*, *complicatedness*, *mindlessness* and *project pathologies*) are suggested having a positive contribution to uncertainty. Ramasesh and Browning (2014) also identify, based on a literature search, items constituting each of the four factors, as presented in Table 3-3.

Most of the literature and theory being investigated in this research work regarding the measurement of perceptual uncertainty reviewed, although recognising the multidisciplinary of uncertainty, have been focused on individual sources, mostly environmental uncertainty, with only a few cases considering the internal environment (Priem, Love and Shaffer, 2002).

Table 3-3 Items constituting the level of uncertainty in project management (Ramasesh and Browning, 2014).

Element complexity	*Relationship complexity*	*Complicatedness*	*Mindlessness*	*Project pathologies*
Number of project elements	Number of relationships among project elements	Lack of encapsulated interactions	Entrapped mindset	Mismatched project subsystems
Variety of project elements	Variety of relationships among project elements	Lack of observer capability	Pathological intensity	Fragmented expertise
Internal complexity of project elements	Criticality of relationships among project elements	Unintuitive system organization	Missing weak signals	Stakeholders' unclear expectations
Lack of robustness of project elements	Internal complexity of relationships among project elements	Lack of observer experience (novelty)	Willful ignorance	Dysfunctional culture
	Externality of relationships	Very large scale-up		
		Divergent viewpoints		

Following the recommendation proposed by Miller (1993) as a response to criticisms regarding the aggregation of scores into a global perceived uncertainty measure (Milliken, 1987) (as found in previous literature), we propose here a disaggregated measure of uncertainty. Derived from strategy, decision-making, (ship) design and uncertainty literature, we decompose perceived uncertainty in five categories, viz. *input*, *model*, *process*, *agent* and *context*; see Figure 3-3. This categorization of uncertainty in five constructs and the corresponding items have been derived from the literature search. Building on what it was initially proposed by Wacker (1998), Ramasesh and Browning (2014, p. 194) suggest that literature review "provides the accepted definitions, applicable domains, previously identified relationships (along with empirical tests), and specific predictions", which supports the definition of our categorization. These five categories represent the elements of a social system model as indicated in Figure 3-3. Although outcome as one source of uncertainty was discussed in the literature as a potential additional construct, we rely on the suggestion of Saunders *et al*. (2013a) that outcome is the result and not a source of uncertainty.

The purpose of this section is, therefore, first to consolidate the particular fragmented and broader theoretical perspectives outlined, reviewed and discussed earlier in Chapter 1 and Chapter 2 of this thesis. Second, it is necessary to develop a theoretical model to consolidate and structure the literature review findings of this thesis. Third, to be able to generate a research hypothesis that focuses on the interplay of uncertainty and efficiency of decision making, with applicability to the ship design framework. Forth, to develop a measurement system to capture the level of uncertainty in ship design processes.

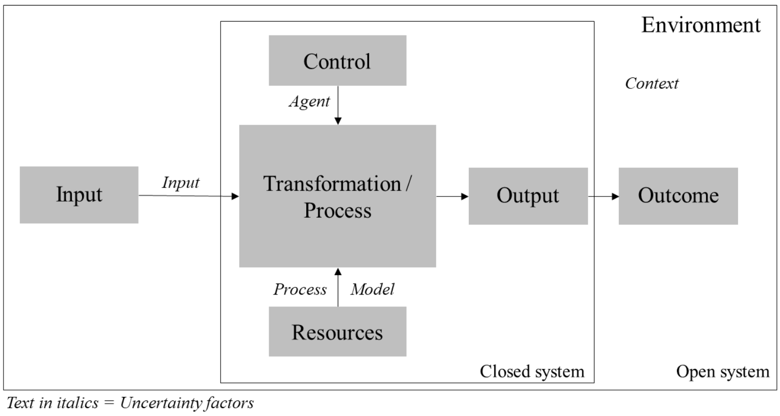


Figure 3-3 Uncertainty factors in a socio-technical system model framework. Adapted from (Brett, 2000).

The five uncertainty constructs predicted from our literature review work: (*i) agent* relates to the self-perception of uncertainty by the different parties or stakeholders involved in the ship design process. It is influenced by professional factors such as interest, motivation, abilities, experience, background and personal factors like attitude, culture, language, tolerance for ambiguity or perception of risk. Based on: (Duncan, 1972; Miller, 1993; Atkinson, Crawford and Ward, 2006; Johansen *et al.*, 2014) In other words, who is involved? (ii) *Context* relates to the unpredictability of changes in the operating environment, including economic, political, social and technological factors as a result of external sources. Changes may be generated directly by customers, competitors, regulators, or indirectly as a result of the global economy or political and geopolitical sources. Based on: (Duncan, 1972; Miller, 1993; Walker *et al.*, 2003; Atkinson, Crawford and Ward, 2006; Saunders, Gale and Sherry, 2013b; Johansen *et al.*, 2014). In other words, what are the external factors influencing the decision? (iii) *Input* relates to the lack of information, lack of understanding, lack of clarity or lack of agreement regarding the salient or relevant issues (goals and expectations) of the vessel project or design. It may be a consequence of the unpredictability of needs, which often leads to limited levels of detail. The input may be seen as a consequence of the ill-structured (or wicked) nature of the decision-making problem. Based on: (Duncan, 1972; Miller, 1993; Walker *et al.*, 2003; Atkinson, Crawford and Ward, 2006; Saunders, Gale and Sherry, 2013b; Johansen *et al.*, 2014). In other words, what is the problem we need to solve? (iv) *Model* relates to the lack of understanding of the system and its relationships; and to the lack of accuracy, quality and reliability of estimates and simulation models. It is influenced by the novelty or lack of experience, as well as the complexity or number of factors taken into account or affecting the decision-making process and the understanding of those. Gass and Joel (1981) name it model confidence and express the trustfulness on the results and the willingness of decision-makers to use the results. Based on: (Duncan, 1972; Walker *et al.*, 2003; Atkinson, Crawford and Ward, 2006; Boschetti, 2011; Saunders, Gale and Sherry, 2013b). In other words, what we use to solve it? And (v) *process* relates, as its name indicates, to the uncertainty generated in the overall decision-making process. It refers to the lack of knowledge of the process (stages); resulting from a poor or insufficient communication among stakeholders. While *input* refers to the lack of information and *model* to the lack of accuracy or understanding, *process* relates to the operationalization of decision-making. Based on: (Fox *et al.*, 1998; Brashers, 2001; Boschetti, 2011; Saunders, Gale and Sherry, 2013b) In other words, how is the problem solved?

An alternative to this uncertainty categorization is proposed by Duncan (1972), who groups the sources of uncertainty above described in the internal environment (including *input*, *model*, *process* and *agent*) and external environment (including *context*). He describes the former as the physical and social factors within the boundaries of the decision-making unit, while the latter would represent those physical and social factors outside the decision-making boundaries. According to the findings from Duncan (1972), the dynamism of the environment (*context*) has a stronger influence on the perceived uncertainty than *model*. The uncertainty generated by the environment is normally, higher than the one resulting from the complexity of the decision-making problem (Duncan, 1972).

Throughout this literature review and theorization work, a number of factors have been identified which influence the proliferation of uncertainty in organizations, design projects or decision problems. In the following paragraphs, the five constructs proposed above are further described and related to previous literature work. A total of 196 items were found in literature as influencing the perception of uncertainty in decision-making situations. These factors were identified in 56 publications, ranging from the early work of Lawrence and Lorsch (1967), Duncan (1972) or Downey and Slocum (1975), to six publications from 2017. Most of the publications, 66%, have been published during the past 10 years. The 196 items have been finally related to 53 factors in our model and those, at the same time, in five uncertainty constructs. The grouping of the 53 factors and the connection of shipping relating factors with factors supported by Cronbach's alpha from other disciplines was done based on the considerations of an expert group of three people.

3.2.1. *Agent* – independent construct

Downey, Hellriegel, and Slocum (1977) assess the effect of individuals in the overall perception of uncertainty. The authors suggest that an environment is not inherently more or less uncertain without the consideration of cognitive factors. Different people will appreciate the same environment with different levels of uncertainty. Culture, and especially its effect on the tolerance to ambiguity have a major influence in the way decision-makers perceive uncertainty

(Duncan, 1972; Downey and Slocum, 1975; Gladwell, 2009; Saunders, Gale and Sherry, 2013a; Iannello *et al.*, 2017) but also how they act in its presence. The effect of culture on the perception of uncertainty and the likelihood of making a decision is further explored by Iyengar (2010). Culture not only relates to the nationality or ethnic group, but also to the specific company and its way of doing business (Weick and Sutcliffe, 2007). Communication has also an important role in the perception of uncertainty in decision-making situations (Brashers, 2001; Thunnissen, 2003; Gladwell, 2009; Ramasesh and Browning, 2014). The communication channel (telephone, email, oral), the language and the ability of the stakeholders with it, affect the effectiveness of communication and the uncertainty induced with it. The use of imprecise terms is an example of this type of uncertainty. In relation to communication, the number of stakeholders involved in the decision-making process will affect negatively on the effectiveness of the communication within the decision group (Brashers, 2001; Gladwell, 2009; Ramasesh and Browning, 2014). The relationship between the parties will also influence the effectiveness of communication (Brashers, 2001; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014). The communication between two stakeholders that have a close relationship and have worked together before will entitle to less ambiguity than that of two strangers.

The experience of the decision-maker in a similar decision situation (Downey and Slocum, 1975; Atkinson, Crawford and Ward, 2006; Brett, Boulougouris, *et al.*, 2006; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014), and his or her skills (knowledge, expertise or capability) (Fredrickson and Mitchell, 1984; Miller, 1993; de Weck, Eckert and Clarkson, 2007; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014; Thanopoulou and Strandenes, 2017) are also expected to influence the perception of uncertainty. March (1994) suggests that the greater the ignorance of those making decisions, or implementing them, the greater the variability of the outcome. Lawrence and Lorsch (1967) suggest that stakeholders may not experience uncertainty outside their areas of expertise and, overall, they might prefer some sources of uncertainty over others (Tversky and Kahneman, 1992). Downey and Slocum (1975) suggest that the role of a stakeholder in an organization or project will affect the trustfulness and beliefs of the other stakeholders, reducing the ambiguity of the information provided by that stakeholder. Thus, information coming from management or an experienced person in the organization will be subject to more trust than if it comes from a summer intern. Table 3-4 includes an overview of the factors integrating the construct *agent*.

Table 3-4 Overview of factors relating to the independent construct agent.

Factors	*Nos. Ref.*	*Sources*
Beliefs	2	(Downey and Slocum, 1975; Liwång, 2015)
Communication	4	(Brashers, 2001; Thunnissen, 2003; Gladwell, 2009; Ramasesh and Browning, 2014)
Experience with projects	5	(Downey and Slocum, 1975; Atkinson, Crawford and Ward, 2006; Brett, Boulougouris, *et al.*, 2006; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014)
Number of stakeholders	2	(Ulstein and Brett, 2012; Saunders, Gale and Sherry, 2013a)
Perceptions	4	(Duncan, 1972; Brashers, 2001; Boschetti, 2011; Thanopoulou and Strandenes, 2017)
Relationships	3	(Brashers, 2001; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014)
Skills	7	(Downey and Slocum, 1975; Fredrickson and Mitchell, 1984; Miller, 1993; de Weck, Eckert and Clarkson, 2007; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014; Thanopoulou and Strandenes, 2017)
Tolerance for ambiguity	5	(Duncan, 1972; Downey and Slocum, 1975; Gladwell, 2009; Saunders, Gale and Sherry, 2013a; Iannello *et al.*, 2017)

3.2.2. *Context* – independent construct

Context, also named environmental uncertainty, is the type of uncertainty that has received the largest interest from the research community, as it can be appreciated from our literature review study. This construct relates to the uncertainty of exogenous nature, and therefore, the decision-makers can influence it to a little extent. *Context* describes all the factors outside the boundary of the design decision-making environment that directly or indirectly influence the outcome of the decisions.

The environment is very sensitive to the type of project, product or decision under evaluation. As an example, the factors considered by Miller (1993) in his study on the installation of a factory in a potentially unstable country will not apply, in most of the cases, to decision-making situations in ship design. A special case is if the shipowner considers building the vessel in unstable countries or countries sanctioned by the United States or the European Union. Some recent examples are Turkey or Russia. On a general bases, supply and demand of products or services are recognised as drivers of uncertainty in most of the literature reviewed, specially in business-related decisions (Mangel and Clark, 1983; Gates, 1984; Wernerfelt and Karnani, 1987; Miller, 1993; Krishnan and Ramasamy, 2011; Niamié and Germain, 2014; Erikstad and Rehn, 2015; Puisa, 2015a; Sumaila, Bellmann and Tipping, 2016; Thanopoulou and Strandenes, 2017). Supply and demand may reflect the general market conditions, such as the world economy, trades, oil prices, etc. In many cases, this variable market condition is modelled separately from supply and demand (Walker *et al.*, 2003; Saunders, Gale and Sherry, 2013a; Niamié and Germain, 2014; Erikstad and Rehn, 2015; Hiekata *et al.*, 2015; Puisa, 2015a; Thanopoulou and Strandenes, 2017). Similarly, supply and demand also contribute to the definition of the revenues and expenses over the lifecycle of a product. In many cases, the dayrates a ship could be expected to get, and the related costs, are also considered explicitly. A special case of the latter is fuel costs, which play a significant role as they represent around 30% of vessel costs in many ship segments. For this reason, many consider only the variable fuel prices rather than total vessel costs (Hiekata *et al.*, 2015; Plessas and Papanikolaou, 2015;

Puisa, 2015a; Jafarzadeh *et al.*, 2017; Kana and Harrison, 2017; Thanopoulou and Strandenes, 2017).

The volatility of shipping markets is one of the principal factors affecting newbuilding activity, Seaman and Smith (2019, p. 1) suggest that "the volatility of wild fisheries - both in terms of supply and price - has been what has put off big food companies or private equities from getting involved". In fishing markets, food companies and private equities are the principal sources of equity and funding for investing in vessel newbuildings.

Regulations also play an important role in the overall perceptual uncertainty in decision-making situations (Miller, 1993; de Weck, Eckert and Clarkson, 2007; Standal, 2008; Saunders, Gale and Sherry, 2013a; Erikstad and Rehn, 2015; Thanopoulou and Strandenes, 2017). Regulation changes such as those relating to the emissions in the shipping industry have shown to have a strong influence in the ship design industry recently (Bouman *et al.*, 2017). Additionally, tax policies (Miller, 1993; Thanopoulou and Strandenes, 2017) and other political constraints in general (Miller, 1993; Walker *et al.*, 2003; Brett, Boulougouris, *et al.*, 2006; Thanopoulou and Strandenes, 2017), such as the stability of the politic system, must be taken into consideration. Other institutions, such as flag states in shipping, also affect the uncertainty in projects (Gates, 1984; Saunders, Gale and Sherry, 2013a; Thanopoulou and Strandenes, 2017). Financial factors including inflation rate, interest rates or exchange rates are of special importance in large projects for international application (Miller, 1993; Erikstad and Rehn, 2015). Disasters such as wars, terrorism or epidemics also represent uncertainty factors in decision-making situations relating to investments. Some examples are described in Sheffi (2015).

Market competition, relating to the actions taken by competitors such as disruptive product, product price changes, or the entry of new firms in the market also generate uncertainty in decision situations (Wernerfelt and Karnani, 1987; Miller, 1993; Krishnan and Ramasamy, 2011). Market dynamism is also considered by many as one of the factors influencing uncertainty. Changes in the market may be a result of market competition, regulations, or disasters. Rehn *et al.* (2018) and Pettersen *et al.* (2018), for example, consider a potential switch from offshore oil & gas (OO&G) to the offshore wind energy generation (OWEG) market. Relating to this last aspect is the consideration of changes in future product or service requirements (Andrews, 2012; Doerry, 2014; Johansen *et al.*, 2014; Gaspar, Brett, Erikstad, *et al.*, 2015; Broniatowski, 2017b). An operation which requires a given capability today may entail additional or alternative capabilities in the future. Alternatively, even if requirements do not change, the performance of the system or the quality of the product may change over time. In most of the cases, the rate of degradation or potential errors is difficult to predict.

The sea state in which the vessel will have to operate over its lifetime is uncertain (Gates, 1984; Hannapel and Vlahopoulos, 2010; Erikstad and Rehn, 2015; Liwång, 2015). Contrary to the operating region, which is decided by the operator of the vessel, the sea state cannot be controlled by the operator of the vessel. Although based on the historical data from the sea states it is possible to estimate the probability of occurrence of a given sea state in a specific region and time of the year. A recent example was the cancellation of a research campaign by the research vessel MV Konpris Haakon due to unexpected ice thicknesses (Borchgrevink-Brækhus, 2019). Table 3-5 includes an overview of the factors integrating the construct *context*.

Table 3-5 Overview of factors relating to the independent construct context.

Factors	*Nos. Ref.*	*Sources*
Competition	7	(Wernerfelt and Karnani, 1987; Miller, 1993; Krishnan and Ramasamy, 2011)
Regulations	8	(Miller, 1993; de Weck, Eckert and Clarkson, 2007; Standal, 2008; Saunders, Gale and Sherry, 2013a; Erikstad and Rehn, 2015; Kana and Harrison, 2017; Thanopoulou and Strandenes, 2017)
Dayrates	6	(Gates, 1984; Millar and Gunn, 1990; de Weck, Eckert and Clarkson, 2007; Erikstad and Rehn, 2015; Kana and Harrison, 2017; Thanopoulou and Strandenes, 2017)
Dynamism	6	(Duncan, 1972; Downey and Slocum, 1975; Miller, 1993; Johansen *et al.*, 2014; Saunders Pacheco do Vale and Monteiro de Carvalho, 2014; Thanopoulou and Strandenes, 2017)
Fuel prices	6	(Hiekata *et al.*, 2015; Plessas and Papanikolaou, 2015; Puisa, 2015a; Jafarzadeh *et al.*, 2017; Kana and Harrison, 2017; Thanopoulou and Strandenes, 2017)
Vessel costs (excl. fuel)	4	(de Weck, Eckert and Clarkson, 2007; Plessas and Papanikolaou, 2015; Puisa, 2015a; Kana and Harrison, 2017)
Future requirements	4	(Andrews, 2012; Doerry, 2014; Johansen *et al.*, 2014; Gaspar, Brett, Erikstad, *et al.*, 2015; Broniatowski, 2017b)
Financial factors	4	(Miller, 1993; Erikstad and Rehn, 2015; Kana and Harrison, 2017)
Institutions	3	(Gates, 1984; Saunders, Gale and Sherry, 2013a; Thanopoulou and Strandenes, 2017)
Market conditions	8	(Walker *et al.*, 2003; Saunders, Gale and Sherry, 2013a; Niamié and Germain, 2014; Erikstad and Rehn, 2015; Hiekata *et al.*, 2015; Puisa, 2015a; Kana and Harrison, 2017; Thanopoulou and Strandenes, 2017)
Political constraints	7	(Miller, 1993; Walker *et al.*, 2003; Brett, Boulougouris, *et al.*, 2006; Thanopoulou and Strandenes, 2017)
Tax policies	2	(Miller, 1993; Thanopoulou and Strandenes, 2017)
Demand	11	(Mangel and Clark, 1983; Gates, 1984; Wernerfelt and Karnani, 1987; Miller, 1993; Fagerholt *et al.*, 2010; Krishnan and Ramasamy, 2011; Niamié and Germain, 2014; Erikstad and Rehn, 2015; Puisa, 2015a; Sumaila, Bellmann and Tipping, 2016; Thanopoulou and Strandenes, 2017)
Supply	6	(Wernerfelt and Karnani, 1987; Miller, 1993; Erikstad and Rehn, 2015; Puisa, 2015a; Thanopoulou and Strandenes, 2017)
Disasters (Wars, terrorism or epidemics)	4	(Miller, 1993; de Weck, Eckert and Clarkson, 2007; Saunders, Gale and Sherry, 2013a; Thanopoulou and Strandenes, 2017)
Changes in product quality	2	(Miller, 1993; Hiekata *et al.*, 2015)
Sea state	4	(Gates, 1984; Hannapel and Vlahopoulos, 2010; Erikstad and Rehn, 2015; Liwång, 2015)

Two examples of how institutions can have a major influence on the success and performance of a vessel newbuilding project are the recent cases of the RoPax company Grandi Navi Veloci (GNV) or the shipping company Fishermen's Finest. The former ordered an "LNG ready" Ropax vessel in China expecting a prompt availability of liquified natural gas (LNG) at the port of Genova. Shortly after the contract, the company was informed by the port of Genova, that LNG would not be available in the port on a short term perspective, forcing GNV to install scrubbers on the vessel to meet IMO's 2020 SOx content (Capuzzo, 2018). For Fishermen's Finest, the uncertainty factor around the delivery of the vessel was regulatory. The vessel, a factory stern trawler built at Dakota Creek Industries, was not entitled to operate in US waters since 10% of its steel had been produced at a European yard, and therefore was not complying with the Jones Act (Washburn, 2017).

3.2.3. *Input* – independent construct

Input relates to the definition of the project (decision-making or design) scope, preferences, goals or needs. Uncertainty relating to the definition of the scope, can be the result of lack of information (Miller, 1993; Saunders, Gale and Sherry, 2013a; Ralph *et al.*, 2017), poor reliability or quality of the information available (Gates, 1984; Miller, 1993; Thunnissen, 2003; Atkinson, Crawford and Ward, 2006; Marusich *et al.*, 2016) or to lack of clarity (Lawrence and Lorsch, 1968; Duncan, 1972; Miller, 1993; Brett, Carneiro, *et al.*, 2006; Saunders, Gale and Sherry, 2013a; Johansen *et al.*, 2014; Ramasesh and Browning, 2014; Thanopoulou and Strandenes, 2017). When ship designers received a tender specification with the expectations of a customer for a new vessel design, they have to make their own interpretation of the data provided, and in most of the cases, the parties arrange workshops for clarification purposes. In many situations, the specification of the vessel and its interpretation rely on rumours. Rumours are commonly used in situations of ambiguity and uncertainty regarding specific information. Rumours can be spread as misinformation, or deliberately (disinformation) (Qazvinian *et al.*, 2011). One example of a rumour in shipbuilding could be, "the maximum overall length to enter the port of Trondheim is 220 m". This information, spread by someone could reach the hears of a shipping company planning the design of a new cruise vessel to visit, among many, the port of Trondheim. In that case, the company will use 220 m LOA as a constraint for the design, limiting the design space for the designer and the overall business case.

On projects relating to systems integrated on a larger value chain, it is important to consider the operating strategy of the vessel (commercialisation, logistics, maintenance, etc) during the definition phase (Miller, 1993; Atkinson, Crawford and Ward, 2006; Ulstein and Brett, 2012; Thanopoulou and Strandenes, 2017). In some cases, these strategies are not defined when doing the conceptual design of the vessel and inducing uncertainty into the initial expectations and constraints to the vessel design. It is not uncommon to order vessels in speculation. The operational region is an important variable in ship design, as it influences the vessel design to a large extent. Vessels to operate in ice infested waters, for example, will require ice strengthening in the hull, potentially a different propeller and de-icing equipment that vessels in other regions will not require. Canals, ports and shallow areas also represent limitations that should be considered in early design phases.

Nutt (2007) identifies an important relationship between the level of detail of the input to the decision and its resulting performance. His findings suggest that quantitatively stated inputs in contrast to qualitative and impressionistic, lead to higher levels of decision results, potentially as a result of the elimination of ambiguities regarding the motivation for action (Nutt, 2007). Table 3-6 includes an overview of the factors integrating the independent construct *input*.

Table 3-6 Overview of factors relating to the independent construct input.

Factors	*Nos. Ref.*	*Sources*
Clarity of project scope	8	(Lawrence and Lorsch, 1968; Duncan, 1972; Miller, 1993; Ward and Chapman, 2003; Brett, Carneiro, *et al.*, 2006; Saunders, Gale and Sherry, 2013a; Johansen *et al.*, 2014; Ramasesh and Browning, 2014; Thanopoulou and Strandenes, 2017)
Lack of information	3	(Miller, 1993; Saunders, Gale and Sherry, 2013a; Ralph *et al.*, 2017)
Operating strategy	5	(Miller, 1993; Atkinson, Crawford and Ward, 2006; Ulstein and Brett, 2012; Thanopoulou and Strandenes, 2017)
Reliability of information	5	(Gates, 1984; Miller, 1993; Thunnissen, 2003; Atkinson, Crawford and Ward, 2006; Marusich *et al.*, 2016)
Operational region	4	(Fagerholt *et al.*, 2010; Choi, Erikstad and Ehlers, 2015; Erikstad and Rehn, 2015; Kana and Harrison, 2017)

3.2.4. *Model* – independent construct

Eisenbart, Gericke and Blessing (2017) on their study of the use of functional models in design, identified five potential strengths or weaknesses of the different models: (i) traceability of design elements, functions and design parameters satisfying them; (ii) comprehension of the system context; (iii) support of (cross-disciplinary) collaboration; (iv) complexity of the model structure; and (v) miscomprehension due to poor formulation of the model. These five aspects contribute to the overall uncertainty perceived by the decision-maker on the use of one, or another decision-making *model*.

The complexity of the vessel design and consequently the *model* describing it, contribute to the overall perception of uncertainty (Peace Cox, 1974; Perminova, 2011; Saunders, Gale and Sherry, 2013b; Antunes and Gonzalez, 2015). This complexity may arise from the functional requirements of the product, intrinsic project characteristics, the choices of technology or the diversity of actors involved (Danilovic and Sandkull, 2005). Complexity, however, plays a double role in the perception of uncertainty. The availability of more information will, in most of the cases, reduce the perception of uncertainty, although, excessive information may increase the complexity of the process unnecessarily, inducing more uncertainty (Ward and Chapman, 2003).

The ability of the models used by the ship designer to calculate installed power, bollard pull or the fuel consumption of the vessel, induce uncertainty in the selection of a final vessel design solution (Meyer, 2002; Atkinson, Crawford and Ward, 2006; Vrijdag and de Vos, 2010; Vrijdag, de Jong and van Nuland, 2013; Plessas and Papanikolaou, 2015). A similar effect has estimations (Thunnissen, 2003; Walker *et al.*, 2003; Atkinson, Crawford and Ward, 2006; Liwång, 2015). Failures and errors may apply in addition to the estimates and the reliability of calculations (Gates, 1984; Walker *et al.*, 2003; Liwång, 2015). The tolerance level of the different elements also plays a role in the perception of uncertainty (Hannapel and Vlahopoulos, 2010; Mallam, Lundh and Mackinnon, 2015). Thus, estimations and calculation relating to elements with high tolerances will be perceived as less uncertain than in more critical ones.

The lack of understanding of the system will affect the ability to model the effects and consequences of decisions in its overall performance (Walker *et al.*, 2003; Saunders, Gale and Sherry, 2013a). Innovation projects, for example, have to rely, in general, on a poorer understanding of the system. For this reason, innovation projects require different tools and strategies to handle uncertainty. The uncertainty generated by innovation and unproven technologies may result in decision-maker choosing worse, but proven design solutions in contrast to better but unproven ones. This is known as the uncertainty effect (Wang, Feng and Keller, 2013).

The modelling of the economic performance of new vessel designs is a critical aspect in conceptual ship design (Mangel and Clark, 1983; Gaspar, Hagen and Erikstad, 2016). The reliability of the system over its lifecycle and the ability to foresee it also contribute to the overall level of uncertainty in ship design decisions (Hockberger, 1976; de Weck, Eckert and Clarkson, 2007; Erikstad and Rehn, 2015). The ability of a vessel to reach a given speed over time, for example, it is related to the maintenance of the propulsion system, the sea state and the fouling in the hull. For parameters where reliability is critical, it is common to use margins or redundancy to palliate the consequences of such uncertainty. Table 3-7 includes an overview of the factors integrating the independent construct *model*.

Table 3-7 Overview of factors relating to the independent construct model.

Factors	*Nos. Ref.*	*Sources*
Complexity	8	(Lawrence and Lorsch, 1967; Duncan, 1972; Jurkovich, 1974; Peace Cox, 1974; Downey and Slocum, 1975; Atkinson, Crawford and Ward, 2006; Perminova, 2011; Saunders, Gale and Sherry, 2013a; Ramasesh and Browning, 2014; Antunes and Gonzalez, 2015)
Calculation capacities	5	(Meyer, 2002; Atkinson, Crawford and Ward, 2006; Vrijdag and de Vos, 2010; Vrijdag, de Jong and van Nuland, 2013; Plessas and Papanikolaou, 2015)
Tolerance	2	(Hannapel and Vlahopoulos, 2010; Mallam, Lundh and Mackinnon, 2015)
Estimates	4	(Thunnissen, 2003; Walker *et al.*, 2003; Atkinson, Crawford and Ward, 2006; Liwång, 2015)
Economic performance	2	(Mangel and Clark, 1983; Gaspar, Hagen and Erikstad, 2016)
Lack of understanding of the system	2	(Walker *et al.*, 2003; Saunders, Gale and Sherry, 2013a)
Operational performance (reliability)	3	(Hockberger, 1976; de Weck, Eckert and Clarkson, 2007; Erikstad and Rehn, 2015)
Innovation	9	(Lawrence and Lorsch, 1967; Miller, 1993; Walker *et al.*, 2003; Atkinson, Crawford and Ward, 2006; de Weck, Eckert and Clarkson, 2007; Boschetti, 2011; Saunders, Gale and Sherry, 2013a; Broniatowski, 2017a; Kana and Harrison, 2017; Thanopoulou and Strandenes, 2017)
Failures/Error	3	(Gates, 1984; Walker *et al.*, 2003; Liwång, 2015)

3.2.5. *Process* – independent construct

Process relates to the contribution to the overall uncertainty on the way in which the decision-making process is carried out. March (1994, p. 177) suggests that during the decision-making process, many actions are happening at once, "in a way that makes their interpretation uncertain and their connection unclear". Lack of a proper understanding of the *process* is an important aspect of ship design. For shipping companies with little or none experience in carrying out shipbuilding projects, the lack of knowledge and understanding of the *process* can be a stopper of the project itself. In these cases, it is common for these companies to purchase the services of a broker or a technical office which have the experience they lack.

Relating the technical design, the lack of knowledge regarding the causal relationships, in other words, how the different systems onboard the vessel interact with each other, or how the vessel interacts with the external environment, is recognised as a limitation for ship designers. It is very difficult to track all the effects of a change in the overall vessel (recall Evan's spiral, where only one aspect of the vessel design was evaluated at the time), although more recently the evolution of computational power has allowed for major improvements in this field. Product changes are changes in the design that may be not recognised or registered and therefore are not accounted for. It is not uncommon that the shipyard starts pricing the vessel based on an old version of the steel weight estimation, and therefore its quotation will not be valid. System integration also relates to this aspect, although on a holistic view. How will the vessel be integrated into a larger value chain? Product lifecycle management (PLM) and product data management (PDM) techniques look for better communication of information within projects, in order to reduce this uncertainty.

Another important aspect relates to the way in which the design alternatives are evaluated. How can the customer or designer know what is a better vessel for them? When should customers and designers stop searching for more alternative designs? Goodness of fit metrics or performance benchmarking can be useful in these cases. In most of the cases, it is difficult for ship owners to define a clear set of preferences for designers to work on, which makes this process more difficult.

Finally, another factor relating to the construction phase of the vessel but with influence on the conceptual design phase is the shipbuilding time. As many vessels start contractual agreements after the delivery of the vessels, the delivery date is a very important factor. In many cases, shipping companies rely on less complex or innovative design solutions to ensure on-time or quicker deliveries. Table 3-8 includes an overview of the factors integrating the independent construct *process*.

Table 3-8 Overview of factors relating to the independent construct process.

Factors	*Nos. Ref.*	*Sources*
Goodness of fit	1	(Ulstein and Brett, 2015)
Lack of knowledge of the process	4	(Lawrence and Lorsch, 1967; Thunnissen, 2003; Stockstrom and Herstatt, 2008; Boschetti, 2011)
Lack of knowledge on causal relationships	3	(Thunnissen, 2003; de Weck, Eckert and Clarkson, 2007; Boschetti, 2011; Ulstein and Brett, 2012)
Product changes	1	(Miller, 1993)
Shipbuilding time	2	(Ulstein and Brett, 2012; Thanopoulou and Strandenes, 2017)

3.3. *Effectiveness in decision-making* – dependent variable

Effectiveness is defined in general terms as "the degree to which something is successful in producing the desired result" (Oxford University Press, 2016). Sproles (2000) proposes the use of measures of effectiveness (MOE), as standards to identify *how well* a solution fulfils its initial goals. MOEs represent the perception of a particular stakeholder or a mutually agreeable among all the stakeholders (Dockery, 1986). To fulfil their purpose, measures of effectiveness should allow comparison among solutions towards the problem fulfilment, both in a quantitative or qualitative way. Similarly, Ji and Dimitratos (2013) state that the decision-making effectiveness captures the level of satisfaction of decision-makers as regards to the objectives and expectations set. MOEs should not be confused with measures of performance (MOP). Sproles (2000) links MOP and MOE with efficiency and effectiveness respectively. While efficiency represents *Doing the thing right!* effectiveness refers to *Doing the right thing!* MOPs express how good a system is performing a function, while MOEs represent how well fulfils the need it was intended for. Hence, MOEs are associated with the problem domain while MOPs with the solution domain (Smith and Clark, 2004). Think on a vessel to transport cargo from point A to B. Speed could be considered as a MOP, where the faster vessel may be categorized as better. On the other hand, since the goal of the vessel is transport cargo, as MOE we may use the combination of speed and cargo capacity, representing the amount of cargo per time the vessel can transport. Hence, a slower but fatter vessel may be seen as better.

The challenged faced by decision-makers is the fact that: (i) the outcome of decisions is mostly unknown until they are realized, and (ii) the outcomes of the alternatives not chosen will never be revealed (McNamee and Celona, 2008). So, how can decision-makers select a better outcome given this intrinsic uncertainty? Facing this dilemma, some authors propose to evaluate decision-making effectiveness based on the effectiveness of the process rather than the outcome (Drucker, 1967; McNamee and Celona, 2008; Buede, 2009). This builds on the hypothesis that decision-makers make good decisions in the desire of maximizing the likelihood of good outcomes and not vice-versa. However, Dean and Sharfman (1996) suggest that there is little evidence that the decision-making process influences the effectiveness of decisions. Buede (2009) discusses the challenge of measuring decision-making effectiveness based on the final outcome due to the effects of the environment on the outcomes' effectiveness. Contrary, Dean and Sharfman (1996) argue that is unlikely that the environment will eliminate completely the influence of the decision-making process in the final effectiveness. Buede (2009) suggests evaluating decision-making effectiveness based on decision-makers' level of understanding regarding the decision. A similar finding was proposed earlier by Druker (1967) and Dean and Sharfman (1996). It is up to the uncertainty management strategy selected during the decision-making process to reduce or eliminate the effects of the environment on the outcome and make this a consequence of the decision-making process only. Thus, measuring decision-making effectiveness based on the effectiveness of the process seems to be the alternative with the strongest support in the literature, and is therefore, the approach followed in this research. In ship design literature, a reference is Mistree *et al.* (1990), who relate the effectiveness of decision-making to the quality, correctness, completeness, and comprehensiveness of the decisions.

The effectiveness of decision making has been studied in different contexts over the years. One of them is education. Building on previous research by Elbanna and Child (2007), Aldhean (2017) evaluates the effectiveness of strategic decision in high education institutions. Based on the responses of 485 participants, the author evaluates the causality between decision effectiveness (dependent variable) and six independent variables (*decision importance*, *rationality in decision making*, *intuition*, *decision decentralization*, *environmental uncertainty* and *organizational performance*). His findings suggest that five of the independent variables have a significant contribution to decision effectiveness, while the effect of decision decentralization was found to be insignificant. Further, *environmental uncertainty* and *organizational performance*, play a moderator role only, influencing the relation between *rationality in decision making* and *decision effectiveness*.

Another example is the work of Ji and Dimitratos (2013), who evaluated decision-making effectiveness among Chinese firms, mostly small- to medium-size enterprises at an early stage of internationalization. The authors studied the causality between entry mode decision effectiveness (dependent variable) and of six independent variable factors, viz. *decision rationality*, *hierarchical centralization*, *environmental uncertainty*, *environmental munificence*, *local experience* and *local linkages*. Their findings rely on 233 responses to a survey. Both, *decision rationality* and *hierarchical centralization* affect decision-making effectiveness, with a weaker and negative direction in the second case. *Environmental uncertainty* presents a moderating role between *decision rationality* and *decision-making effectiveness*; although always positive, the relationship is stronger for lower levels of *environmental uncertainty*. *Environmental uncertainty* also moderates the effect of *hierarchical centralization*, confirming that higher centralization leads to lower effectiveness in uncertain environments.

Weick and Sutcliffe (2007) suggest that part of the effectiveness of organizations lies in their ability to bring together all the parties involved in a project or initiative. Elbanna and Child (2007) carried out an investigation on the effect of three decision-making dimensions, viz. *rationality*, *intuition*, and *political behaviour*, in the effectiveness of the decision-making process. They based their research on managers from Egyptian companies. The analysis included seven control variables, named decision importance, decision uncertainty, decision motive, environmental uncertainty, environmental hostility, firm's performance and company size.

The constructs identified in the above paragraphs by previous research on decision-making effectiveness are used as bases to define the dependent variable decision-making effectiveness of this research. In most of the previous literature studied, the reliability of the constructs was made available. The reliability levels found in previous studies for the constructs used in our research model are indicated in Table 3-9.

Table 3-9 Constructs of the dependent variable decision-making effectiveness.

Dependent variable constructs	Source	Cronbach's alpha (α)
Rationality	(Dean and Sharfman, 1996) (Ji and Dimitratos, 2013) (AlDhean, 2017)	.800 .770 .840
Decentralization	(Ji and Dimitratos, 2013) (AlDhean, 2017)	.740 .750
Intuition	(AlDhean, 2017)	.780
Local experience	(Ji and Dimitratos, 2013)	.700
Local linkages	(Ji and Dimitratos, 2013)	.720

An alternative research current relates to the term *decision quality* rather than decision effectiveness in relation to the goodness of a decision process (Howard and Abbas, 2000; McNamee and Celona, 2008; Matheson and Matheson, 2016). Mcnamee and Celona (2008) describe decision quality as a combination of *content quality*, characterized by the use of systematic processes and analytical tools, and *people quality*, described by the use of the right human resources. Each of these two constructs is described by the aggregation of six elements (Howard and Abbas, 2000; McNamee and Celona, 2008): (i) appropriate frame, (ii) creative, doable alternatives, (iii) reliable information, (iv) clear preferences, (v) correct logic, and (iv) commitment to action.

3.4. Control variables

Working experience has proved to influence decision-makers perception and behaviour under uncertainty (Downey, Hellriegel and Slocum, 1977; Iannello *et al.*, 2017) Höllermann and Evers (2017) found that uncertainty awareness and handling increase with working experience. These two authors find that factors such as the type of employer, educational background or business units have also influence on how uncertainty is perceived and treated in decision-making. As such, they found remarkable differences in how scientists and practitioners cope with uncertainty, and also what type of uncertainties they focus their interest on.

Considering the influence of personal factors in the perception of uncertainty, a set of control variables is introduced to control the bias of factors such as working experience or background: (1) overall experience, (2) the experience in ship-related industries, (3) experience with newbuilding projects, and (4) the role in the newbuilding project. Further, we asked a set of questions relating to the newbuilding project itself, including: (5) vessel type, (6) newbuilding strategy, (7) vessel ownership and (8) operating strategy.

3.5. The research model of this study

There are no complete research models available in the literature reviewed in this research work that cover the problem at hand. Such a model will be used to study the effect of uncertainty on the effectiveness of the decision-making process in conceptual ship design. Hence, it was considered necessary to develop an investigative model to explore the research question of this research work. Our final investigative model is presented in Figure 3-4. The independent variable *uncertainty in ship design* consists of five independence factors extracted from literature. The dependent variable *effectiveness in decision-making* is, however, based on previous research models with proven reliability measures.

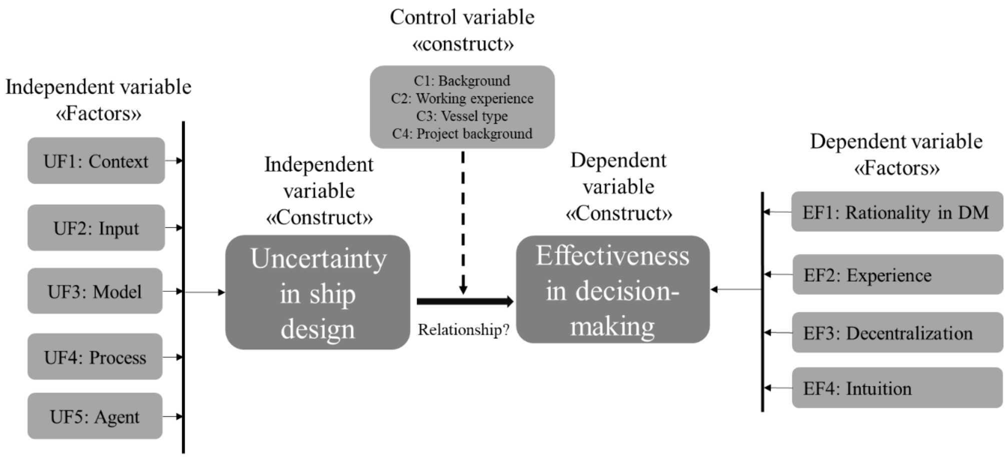


Figure 3-4 Proposed investigative model.

The investigative model presented in Figure 3-4 is the foundation of this research study. Building on this research model, we have defined, a priori, the expectations about the results of the study, which are defined in the form of research hypotheses. A research hypothesis is a testable proposition about the possible outcome of the research study, and are usually derived from the stated research questions and the problems being investigated (Weick, 1995; Kalaian and Kasim, 2008). After the research hypotheses are stated, inferential statistical methods are used to test these hypotheses to find answers to or support for the research questions and make conclusions regarding the research problems at hand.

Building on the literature review and the theorization work carried out as part of this research, five, a priori, content characteristics of uncertainty in conceptual ship design were identified. For each of the content characteristics one hypothesis was formulated (H1 to H5). All the five alternative hypotheses propose that the greater the intensity of the five content characteristics of uncertainty in conceptual ship design, the lower the decision-making effectiveness of the design process. One additional hypothesis H0 (or null hypothesis) was inverted from theory propositions. The six hypotheses in conjunction suggest the following proposition:

The lower the design decision-making uncertainty is positively associated with effective decision-making in vessel conceptual design processes.

A null hypothesis plus five additional hypotheses extracted from this literature and theorization review are tested based on the data collected through the survey instrument.

H0: There is no positive relationship between low design decision-making uncertainty and effective decision-making in vessel conceptual design processes.

H1: Better understanding of decision-making *context* is positively associated with effective decision-making in vessel conceptual design processes.

H2: Better understanding of decision-making *input* is positively associated with effective decision-making in vessel conceptual design processes.

H3: Better understanding of the decision-making *model* is positively associated with effective decision-making in vessel conceptual design processes.

H4: Better understanding of the decision-making *process* is positively associated with effective decision-making in vessel conceptual design processes.

H5: Better understanding of the decision-making *agent* is positively associated with effective decision-making in vessel conceptual design processes.

Similar research has already been studied in other contexts, as for example the study of product development carried out by Stockstrom and Herstatt (2008, p. 481), who suggests that “The more the uncertainty about the market and technology is reduced during the front end, the lower the deviations from front-end specifications during the following project execution phase and higher the product development success”. Similarly, Hillson (2002, p. 235) suggests that “It is also widely recognized and accepted that successful management of uncertainty is intimately associated with project success”. Further, Matheson and Matheson (2016, p. 122) suggest that “Decision quality [here treated as decision-making effectiveness] requires a strategic perspective that accounts for uncertainty and untangles the subtleties of complex systems”.

Substantial support was found in the literature that a high level of uncertainty has a negative effect on decision-making effectiveness. This can be formulated in the following mathematical expression: the Function (F) of decision-making effectiveness (dme) is influenced by (←) a function (f) of the sum (∑) of the intensity (Δ) of the uncertainty (unc) five (1-5) factors. Without saying anything about what type and strength of the relationship that exists between the independent and dependent variables we can develop the following expression presented in Figure 3-5.

$$f\left(\sum \Delta unc_{1-5}\right) \xrightarrow{?} F\left(\sum \Delta dme_{1-4}\right)$$

Figure 3-5 Mathematical expression of the explanatory relationship between the dependent and independent variables of this research model.

Our research model, proposed in Figure 3-4, provides a foundation to measure the relationship between uncertainty and decision-making effectiveness in conceptual ship design processes. Yet, we lack a procedure and methodology to collect data that will enable us to investigate the above-proposed model. The methodology chapter explores different avenues to collect, structure and analyse data and proposes an adequate methodology for this research study.

4. Research methodology

This methodology chapter includes a description of how the research work has been carried out, and how the selection and application of the research approach took place. When starting a new research project, one should keep in mind that research is not just about gathering information and facts and incorporating them into one or more papers. Research is about finding an answer to a question that hasn't been answered before (Leedy and Ormrod, 2015). Hence, we start this chapter by recalling the research question of this thesis work: What are the important uncertainties in conceptual ship design, and how do they influence effective decision-making?

The first four steps of the research cycle (see Figure 4-1) have already been carried out in Chapter 1. The purpose of this methodology chapter is to carry out step 5, by developing a specific plan for analysing the problem and its subproblems. Finally, steps 6 and 7 regarding the collection and analysis of data and interpretation of results are carried out in Chapter 5 of this thesis.

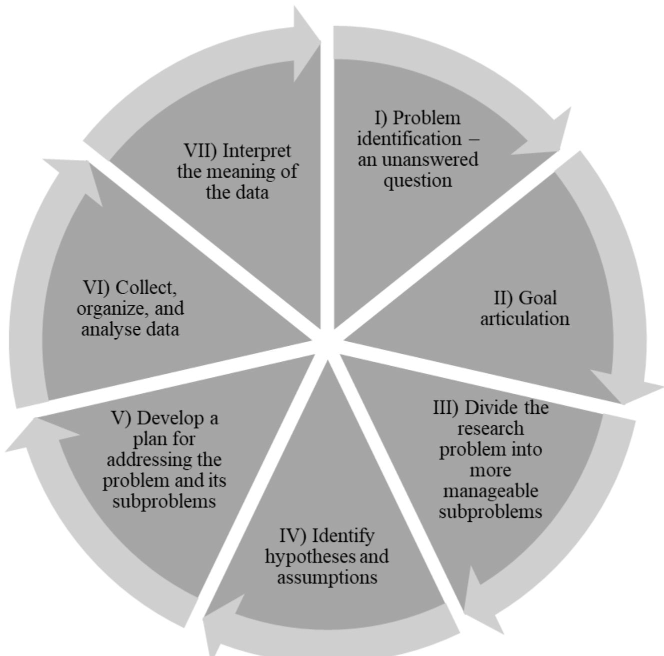


Figure 4-1. The research cycle. Adapted from (Leedy and Ormrod, 2015, p. 21).

Before introducing to the details of research methodology and techniques, it seems appropriate to present a brief overview of an appropriate research process. The research process consists of a series of actions or steps necessary to effectively carry out research and the desired sequencing of these steps. Similarly to Leedy and Ormrod (2015), Kothari(2004) suggests that a typical research process consists of seven (I to VII) closely related activities, which overlap continuously rather than following a strictly prescribed sequence. At times, the first step determines the nature of the last step to be undertaken. If subsequent procedures have not been taken into account in the early stages, serious difficulties may arise which may even prevent the completion of the study. One should remember that the various steps involved in a research process are not mutually exclusive, or they are separate and distinct. They do not necessarily follow each other in any specific order and the researcher has to be constantly anticipating at each step in the research process the requirements of the subsequent steps. However, the following order concerning various steps provides a useful procedural guideline regarding the research process: (1) formulating the research problem; (2) extensive literature survey; (3) developing the hypothesis; (4) preparing the research design; (5) determining sample design; (6) collecting the data; (7) execution of the project; (8) analysis of data; (9) hypothesis testing; (10) generalisations and interpretation, and (11) preparation of the report or presentation of the results. In order to understand the importance of selecting an appropriate research approach, design and methods are necessary a deeper understanding of what is the role of the methodology within the research framework is needed. As suggested by Crotty (1998), as a starting point, the researcher should develop a research proposal answering what methodologies and methods will we be employing and how to justify this choice and use of methodologies and methods.

According to the Oxford Dictionary (2016), research is “the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions”. According to other authors, research is defined as: “systematized effort to gain and apply new knowledge” (Redman and Mory, 1933, p. ix), “movement from the known to the unknown” (Kothari, 2004, p. 1), “discover answers to questions through the application of scientific procedures” (Selltiz *et al.*, 1959, p. 2); we can synthesize research, on a common base from the previous definitions, as an organized process of gaining new knowledge. The categorization of research as a systematic, organized or scientific process, in one way or another, evoke to its structured basis. Research is presented as a cyclical process (Leedy and Ormrod, 2015) consisting, in general, on problem identification, formulating a hypothesis, collection and analysis of facts or data and reaching certain conclusions, either solution to the problem or generalizations for some theoretical formulation (Kothari, 2004).

Research methodology may be understood as “the body of knowledge concerned with the techniques necessary for gathering quality information” (Peace Cox, 1974). It includes the various steps that are generally adopted by a researcher in studying a research problem along with the logic behind them. First of all, it has to be considered that methodologies are neither appropriate nor inappropriate until they are applied to a specific problem (Downey and Ireland, 1979). It is a concern of the context where they are applied (Brett, 2000), the nature of the research problem (Creswell, 2014) and its purpose (Bloomberg and Volpe, 2008). When selecting a research methodology we look for a process supporting the fulfilment of the research purposes and find answers for our research work (Crotty, 1998).

The approach to research involves three components: research methods, research design or procedures and philosophy (Creswell, 2014). The selection of a research approach will, therefore, involve the use of some specific research methods, following a set of research design and with a specific philosophical view. There are some discrepancies regarding the classification of research approaches, while some authors recognize two basic approaches:

qualitative and quantitative (Kothari, 2004), other authors identify a third type as a combination of the first two, mixed methods (Creswell, 2014). Often the distinction between quantitative and qualitative research is framed in terms of using words (qualitative) rather than numbers (quantitative) (Creswell, 2014) or subjective assessment (qualitative) rather than rigorous quantitative analysis (quantitative) (Kothari, 2004). Qualitative research looks for exploration of a topic, while quantitative investigates cause-effect phenomena (Bloomberg and Volpe, 2008). Creswell (2014) further decomposes quantitative approaches into inferential, experimental and simulation approaches. Downey and Ireland (1979) expand upon the differences among quantitative and qualitative approaches and critic the categorization of the latter as unscientific. According to the authors, the subjectivity that categorizes qualitative approaches has led to the prioritization of quantitative, objective assessment. They avow for the validity and need for quantitative approaches based on the premise that the objectivity required in scientific inquiry is the one from the researcher, not from the ones being the object of research.

Following the order proposed by Saunders *et al.* (2009) in their research onion, the first decision, that relates to the far most layer in Saunder's research onion, is the selection of research philosophy. Thereafter, we are guided towards the internal layers of the onion and narrowing down the alternatives among which we can choose regarding approaches, strategies, choices, time horizons and finally techniques and procedures to collect and analyse data. The selection of research philosophy and successive stages are described in the sections below.

4.1. Metaphysical positioning of the research work

The human factor (social science) referred to as worldview (Guba, 1990; Creswell, 2014), paradigms (Burell and Morgan, 2005; Lincoln, Lynham and Guba, 2011) or epistemologies and ontologies (Crotty, 1998), collects the influence of philosophical ideas, beliefs and practices that guide the action (Guba, 1990) that the researcher brings to the research work. Although philosophical ideas very often remain largely hidden in research (Slife and Richard N. Williams, 1995), they still influence the practice of research and need to be identified (Creswell, 2014). It is, therefore, useful to consider the underlying philosophies of research to determine the most appropriate research design given the research question in this research work (Clark, 1972; Oliga, 1996; Brett, 2000; Leedy and Ormrod, 2015).

At this point, there is not an agreement regarding the types and number of paradigms. Burell and Morgon (2005) identify four paradigms: functionalist, interpretative, radical-structuralist and radical-humanist, while Lincoln, Lynham and Guba (2011) identify positivist, postpositivist, constructivist, critical theory and participatory. Similarly, Bloomberg and Volpe (2008) define another four paradigms, named: postpositivism, critical theory, social constructionism and pragmatism. Four are also the paradigms defined by Creswell (2014), postpositivism, transformative, constructivist and pragmatic. Table 4-1 includes an overview of the paradigm classification by several authors.

Table 4-1 Classification of research paradigms.

(Burell and Morgan, 2005)	(Lincoln, Lynham and Guba, 2011)	(Bloomberg and Volpe, 2008)	(Creswell, 2014)	(Saunders, *et al.*, 2009)
Functionalist	Positivist / Postpositivist	Postpositivism	Postpositivism	Positivism
Radical structuralist / Radical humanist	Critical Theory	Critical Theory	Transformative	Realism
Interpretative	Constructivism	Social constructionism	Constructivist	Interpretivism
	Participatory/Cooperative	Pragmatism	Pragmatic	Pragmatism

These categories are not static or fixed, therefore, the researcher has the freedom to incorporate multiple perspectives in his or her research (Lincoln, Lynham and Guba, 2011). Lewis and Grimes (1999, p. 672) argue on the advantages of meta-triangulation, as a strategy of applying paradigmatic (philosophic) diversity to foster greater insight and creativity".

The research question in this research work suggests that uncertainty is an element that can be measured. This statement supports a positivist philosophy, which suggests that the social world exists externally and should be measured through objective methods and not based on intuitions or sensations. Positivisms is also referred to as the quantitative research (Bloomberg and Volpe, 2008). Positivism, therefore, is supported by the belief that reality is external and objective, and that knowledge is only of significance if it is based on the observations of this external reality. Thus, this research work is based on a positivist worldview.

After five years working as a business analyst, I am more comfortable exploring and looking for answers to problems building on the use of data. So far, I haven't found a problem in my daily tasks that could not be measured or explained by numbers. Thus, it was natural to select positivism as my metaphysical position and principal paradigm for this research.

4.2. Research approach

The research question proposed in this research is explored using a multi/mixed-method denominated exploratory design research (Leedy and Ormrod, 2015). It consists of exploring a phenomenon based on a qualitative evaluation and then probing quantitatively the extracted hypothesis (Subedi, 2016). The initial analysis requires a deep evaluation of uncertainties in the ship design domain as perceived by the different actors involved in the conceptual design phase of new ships. An extensive literature review study was carried out, and presented in Chapter 2, to explore the role of uncertainty in ship design decision-making. Further, in Chapter 3 of this thesis, we explored previous research on the quantification of uncertainty and the research models used in alternative industries and contexts. None of the existing proposed research models in the literature was considered adequate for this research. Some of those models were limited to the study of environmental uncertainty, and others were focused on research problems that were not relevant to our research work, such as medicine. Therefore, it was necessary to develop a new investigative model.

The first stage of the development of our research model was to identify factors categorizing uncertainty. In Section 3.1, we suggest five classifications of uncertainty depending on its source, nature, time dimension, level and category. The classification by source provided a good foundation to develop our research model, since some of the factors like *context* or *agent*, were included in already existing research models. Each of the five uncertainty factors was defined by a set of items that, according to previous literature, were relating to them. Items from research work outside ship design were adapted to ship design jargon. The dependent variable was, on the other hand, taken from previous research studying decision-making effectiveness. Thus, the factors used in the dependent variable were validated by Cronbach's alpha from previous research studies.

A questionnaire was developed to supply the necessary quantitative data to test our research model. The development of the questionnaire is described in Section 4.4, and its analysis and results are commented in Chapter 5 of this thesis.

4.3. Research method

For this research, we will use a multicriteria regression analysis as the principal methodology to study our research question. Regression analysis is the most common and versatile dependent technique used for research in decision-making (Hair *et al.*, 2010). In general, multicriteria regression analysis is used to analyse the relationship between one dependent variable (Y) and several independent variables (X). In multicriteria regression analysis, the predictor independent variables (X) are used to predict the value of the single dependent variable (Y). Additionally, multicriteria regression analysis can be used to seek for an explanation of the change in the independent variable. Each of the independent variables will have a contribution (magnitude, sign and statistical significance) to changes in the dependent variable. This contribution is defined by the weights associated with each predictor, which are extracted from the regression analysis. The set of weighted predictors (independent variables) forms the regression variate. A basic formulation is presented in Equation 7. The terms b are the regression coefficients and represent both, the type of relationship (whether positive or negative) and the strength of it. The value of the coefficients represents the change in the dependent variable for each unit of change in the predictor.

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_n X_n \qquad \text{Equation 7}$$

The process of carrying out a multicriteria regression analysis can be described as a set of six successive stages (Hair *et al.*, 2010). The first three stages consist of the structuring of the problem, data gathering and data validation, and the remaining three stages represent the analysis of the data, its interpretation and its validation (Figure 4-2).

The starting point of multiple regression analysis is the research problem, and the selection of a research model to study it (stage 1). In our study, the research model has been defined based on previous literature and discussed in the theorization chapter of this thesis. This follows the recommendations of authors like Hair et al. (2010) who suggest that the definition of variables and factors shall be done based on conceptually or theoretical grounds. Ideally, the research model should be built based on previous research models, where the researchers have statistical data supporting the reliability and contribution of the variables (Brett, 2000). Although for this research we couldn't find relevant material, the selection of variables and factors were still supported on the theoretical ground and expert judgment.

With a research model in place, the next stage (stage 2) is to populate the model with data. In this research, the data has been gathered through a survey process which is described in the next section of this thesis. Surveys are useful for studying a large number of variables using a large sample size and rigorous statistical analysis techniques. They normally provide greater external validity and easier generalisation of result than other methods (Premkurean and King, 1994). Case studies, on the other hand, are good for capturing the richness of the process dimension and are appropriate when research and theory are in very early stages and only smaller sample sizes are available and generalisation of results are not a major concern to the research in question (Brett, 2000). The size of the sample (number of observations) directly influences the appropriateness and the statistical power of the multiple regression (Hair *et al.*, 2010). Neither small nor large samples are desired as they become overly sensitive to statistical significance. The size of the sample affects statistical significance must be considered when interpreting the results. As a rule of thumb, the literature suggests to consider 15 to 20 observations for each independent variable; and should never fall below 5 (Hair *et al.*, 2010). Thus, considering that our research model consists of 5 independent variable, the objective of the survey instrument is to capture 75 to 100 observations, and not less than 25. If the sample is below the recommended 5:1 ratio, the generalization of results becomes questionable (Hair *et al.*, 2010).

The third stage (stage 3) of the process of a multivariate regression analysis consists of ensuring the compliance of a set of assumptions necessary to rely on the results of the regression analysis. These assumptions affect both, the independent variables as single units, but also to the whole. The compliance of these assumptions is explored in Section 5.2 of this thesis. Under a lack of compliance of this set of assumptions, the researcher will not be able to identify if errors in prediction are a result of an actual lack of relationship among the variables, or they are a result of the characteristics of the data. In the next chapter, each of the assumptions is further described and explored. Both, graphical and mathematical techniques are used to support the compliance of these assumptions.

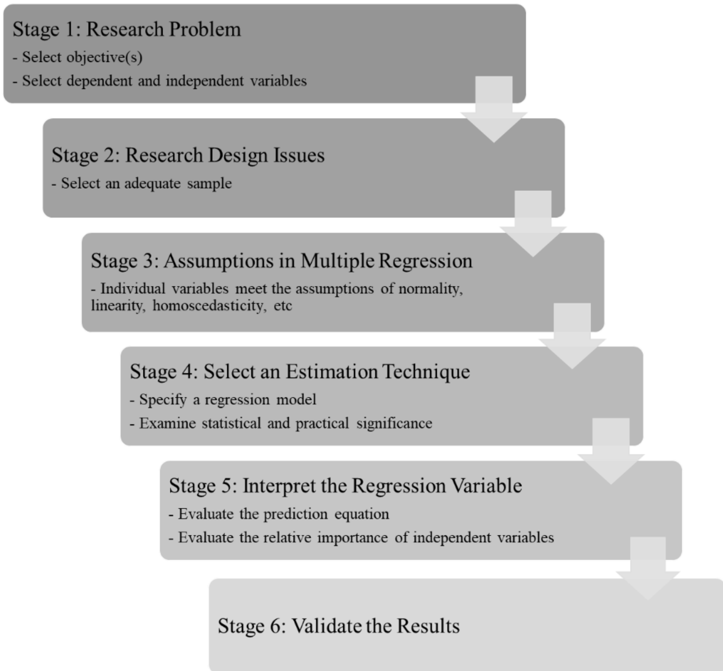


Figure 4-2 Stages 1 to 6 in a multivariate regression analysis process. Adapted from (Hair *et al.*, 2010, p. 164;183).

Stage 4 consists of the actual analysis of the predictive power of the independent variables and the definition of the regression model. At this stage, the research model has been populated with data and calibrated so all the assumptions necessary to avoid bias and inaccurate predictions are compliant. There are three approaches among which the researcher can specify the research model: (i) confirmatory, (ii) sequential and (iii) combinational processes (Hair *et al.*, 2010). The confirmatory is the simplest although perhaps most demanding approach. The confirmatory approach, as its name indicates, is used to confirm a research model with a predefined set of independent variables. On the other hand, sequential methods selectively add or delete independent variables exploring for a sufficient and acceptable regression model. This approach is useful to identify an effective regression, looking for a combination of variables that maximizes prediction with the smallest number of variables. Stepwise estimation is one type of sequential search. In this approach, the researchers include sequentially independent variables in the regression based on their partial correlation coefficients; higher first. However, these approaches require a higher number of observations. Backward elimination and forward addition, also sequential methods, are trial-and-error processes for finding the best fitting regression. Compared to confirmatory approaches, stepwise estimations require observations in the range of 50:1 (Hair *et al.*, 2010). Finally, the researcher may decide to explore all the combinations of independent variables following a combinational approach.

Whatever approach is used to arrive at a regression, the next natural step is to calculate the significance of the model. The coefficient of determination (R^2) measures the proportion of the variance of the dependent variable that is explained by the independent variables. One of the challenges of using R^2 is the fact that it will increase when adding more variables, even if these are non-significant. The adjusted coefficient of determination (adjusted R^2) includes a correction factor accounting for the number of independent variables and the size of the sample. As a supplement to the coefficient of determination, the researcher can use the F-ratio. This ratio indicates if the variation explained by the model is more than the baseline prediction (Hair *et al.*, 2010). Thus, a high F indicates that the regression has a significant value explaining the dependent variable.

The interpretation of the results is naturally the next step (stage 5). The regression coefficients (b) are indicators of the impact and importance of the different independent variables for explaining changes in the dependent variable. However, the researcher should be careful when interpreting these coefficients, since the scale of the independent variables also plays a role in the overall effect. Hence, if the independent variables are not incomparable scales, the direct interpretation of the regression coefficients can be misleading. One way for solving this challenge is the standardization of the regression coefficients. The beta coefficients (β) represent a standardized regression coefficient where all independent variables have a common scale and variability. Thus, the researcher can evaluate which of the independent variables is more important by comparing their betas.

The last and remaining stage (stage 6) at this point is to validate the results. This means, ensure that the regression model represents the general population (generability) and is appropriate in the situations in which it will be used (transferability) (Hair *et al.*, 2010). A direct way for validating the results of multivariate data analysis is to compare the results with previous theoretical models already validated. Are the results in line with previous literature? And if not, are there any reasons that could explain the deviations? However, previous theoretical models are not always available. In those situations, the most appropriate empirical validation approach is testing the regression model on an alternative sample of the same population (Hair *et al.*, 2010).

Although the evaluation of decision-making effectiveness, due to its relation with the context environment, could have been carried out based on a longitudinal study (Hart and Banbury, 1994; Dean and Sharfman, 1996). This alternative has been discarded in this research work due to lack of time. Nonetheless, it is recognized that there may be certain benefits of performing such an analysis.

4.4. Survey instrument

In the following paragraphs, we study the factors influencing the development of a survey instrument. The purpose of our survey instrument is to produce empirical raw data and corresponding statistics, based on the quantitative or numerical descriptions of the perception of uncertainty and decision-making effectiveness by the participants in the survey. The questionnaire is the tool allowing this. Building on our investigative model and the list of factors into each of the constructs, we have to define a list of questions capturing the insights that will allow us to answer our five plus one hypotheses. The quality and validity of the results will depend, to a large degree, on the survey instrument (Fowler, 1993), the questionnaire. In writing the questionnaire, we have followed the guidelines proposed by several authors (Fowler, 1993; Patten, 2001; Diem, 2002; Siniscalco and Auriat, 2005).

The first step consists of the selection of the type of survey. There are multiple types of survey for non-experimental design (Denzin, 2009): (i) one-shot case study: random sample of a group of subjects exposed to a specific event; (ii) one-group pre-test-post-test design: two sets of observations are carried out to the sample group, before and after the exposure to the specific event. The lack of a control group restricts extrapolation since there is no information regarding what would occur if not exposed to the event; and (iii) static-group comparison (ex-post facto): in this case, the researcher evaluates, in a single observation, two groups of subjects. One of the groups has been exposed to a specific event and the other not. One-group pre-test-post-test design is superior to the one-shot design due to the repeated observation. However, problems raised by repeated observation are best resolved by the use of a control group (Denzin, 2009). The static-group comparison should be typically preferred, because it involves the use of comparison groups, although it lacks before measures.

At this stage, and before getting into the definition of our research questionnaire, it is necessary to define our level of analysis and unit of analysis. The level of analysis relates to the context and the level in which the analysis is carried out. Table 4-2 includes an overview of the characteristics of the survey instrument. Unit of analysis, on the other hand, relates to the entity to be studied. Although related, the choice of a level of analysis does not necessarily imply the selection of a specific unit of analysis (Yurdusev, 1993). When establishing a level of analysis, we position our research in a specific context. Although several authors have proposed different categorizations, we take as reference the three levels proposed by Buckley (1967), further categorized by (Yurdusev, 1993) as philosophical, theoretical and practical. The former aspect, philosophical level, consist of the general beliefs and assumptions describing the background of the subject in question. The second aspect, theoretical level, represents a more precise description, including the definition and selection of the boundaries for our analysis. Finally, the practical level includes practices, work, and aspects of everyday reality. It is not essential to include the three levels in a specific analysis. Hence, the researcher may be considered only one of the three levels becoming a philosophical, theoretical or practical analysis (Yurdusev, 1993). In our research, we may consider the study of uncertainty, in general, therefore selecting a philosophical level. Further, and increasing the level of detail, we may consider evaluating the perception of uncertainty, at a theoretical level. In our case, to increase the level of precision and facilitate the connection with industrial practices, we will study the perception of uncertainty during the design process, hence, our boundary conditions are defined as the perception of uncertainty between the starting of the design process up to the signature of the newbuilding contract. It is important to position the respondents to the survey in this frame, so it captures the information that is expected.

After the level of analysis has been described and specified, we can select the unit of analysis. Unit of analysis is the entity that will be the object of research. Researchers on social science propose three units of analysis: the individual person, the society and the universe (Yurdusev, 1993). In our specific research, these three units would represent a single vessel, a fleet of vessels or the entire worldwide fleet. Our unit of analysis is the single vessel, more specifically, our analysis will consist of the latest newbuilding project which the respondent has been involved in or related with. Hence, we are also limiting the time dimension in which the projects have taken place.

Table 4-2 Characterization of the survey process.

Level of analysis	
Philosophical	Uncertainty
Theoretical	Perception of uncertainty
Practical	Perception of uncertainty in conceptual ship design
Unit of analysis	Latest (vessel) newbuilding project
Target population	
Vessel type	All vessel types
Stakeholder	Shipowners, operators and managers
Role within the project	Financial manager and technical manager
Timespan	Indirectly defined by the unit of analysis. The latest newbuilding project the respondents have been involved in

Further, it is necessary to select the targeted population, our sample (Fowler, 1993). This should be reflected in the selection of the demographic questions, but also on the way of how questions are written. We are initially targeting ship owners, as one of the stakeholders involved in the design of a new vessel, and as the direct customer of ship design firms. IHS Fairplay (2018) accounts for more than 44 000 ship owning companies with vessels in operation or under construction. The number goes down to around 21 000 when considering only those with vessels of length overall (LOA) of 50 m or more. Yet, it is not realistic nor plausible to include the entire sample in our analysis. There are three reasons for it: availability of relevant contact information of the company (not all the companies have relevant contact information publicly available), sharing of personnel between companies (the structure of some shipping companies relies on registering each vessel), or group of vessels, under a different ship owning entity, and resource and time limitations (although the questionnaire will be electronically distributed, it requires time and resources to distribute it and follow up). Further, the selection of a language for the distribution of the survey may limit the relevant sampling for the study. Considering that shipping is an international business, we have selected English as the language for our survey, reducing, therefore, the probability of non-response due to language problems. However, this could also induce potential errors as most of the respondents will not have English as a mother language. Fowler (1993) suggests that, when defining the sample for the survey, it should be kept in mind that its adequacy is not dependent on the fraction of the population included, rather on how it has been selected. A sample of 150 may describe with the same accuracy as a population of 1 500 or 15 million (Fowler, 1993).

Following suggestions by Huber and Power (1985) and Dean and Sharfman (1996), the questionnaires should target the persons most deeply involved with the decisions. Based on our experience in ship newbuilding projects, it has been selected the newbuilding project manager, representing the technical and operational perspectives of the customer and the chief financial officer, representing the commercial perspective of the project. The use of more than one interviewee per newbuilding project is also recommended by Huber and Power (1985) and Miller (1993), capturing more than one perspective and potentially offset biases. The selection of respondents in management positions can carry some challenges. Because of their busy agendas, managers may be less willing to spend time in questionnaires, especially if they do not see a potential benefit from it (Huber and Power, 1985). Ensuring the anonymity and confidentiality of responses is a positive step to make respondents more comfortable and increase their interest in responding to the survey (Dean and Sharfman, 1996). To generate interest to the respondent is also positive with regards to response ratio. Huber and Power (1985) suggest explaining in the introductory letter to the survey how the specific research can be useful for the respondents, the researcher, and in general the benefits for the research field.

Surveys are typically characterized by low return rates (Brett, 2000) (between 5 to 15%). Thus, a large initial sample is required in order to achieve a meaningful response and data sample to work with. Low response rates can indirectly produce bias since maybe just subjects with a strong connection with the topic or with the closest relation to the researcher participate. Several researchers emphasize the importance of following up the contact with no respondents (Dillman, 1978; Fowler, 1993). Dillman (1978) suggests sending a reminder to all the nonresponding after 10 days, emphasizing the importance of their answers and the overall results from the study. A similar remind is suggested in the following 10 days after the first remind. Some alternative strategies are also recommended in the literature for increasing the response rate, viz. phone calls (Brett, 2000), topic salience and social network sponsorship (Regan, 2012). The use of incentives or prizes as gratitude may contribute positively to improve the response rate as well.

The delivery method does also influence the response rate. In their research, Hardigan, Popovici and Carvajal (2016) compared postal mail, email and hybrid approaches, finding that postal mail represented the lowest cost per completed response. Yet, it is the highest time-consuming approach, as it inquires waiting time from delivery of questionnaire until its reception, while computer-based surveys are instantaneous (Fowler, 1993). Similarly, the information received from mail surveys have to be computerized, which induces a risk of misreading responses, and therefore errors in the final results. Together with the cost and speed reduction, Fox *et al.* (2003) identify anonymity and access to larger and more diverse samples, as two additional strengths of web-based questionnaires. In addition to the low return rate, answers will be exposed to misunderstandings or misinterpretations of the questionnaire (Leedy and Ormrod, 2015), making questionnaires better for objective evaluations (Patten, 2001). In this case, uncertainty could easily be misinterpreted as a risk. A last disadvantage of questionnaires is that the answer could be influenced by social desirability (Patten, 2001), resulting in socially-accepted responses rather accurate.

Developing a survey instrument involves three essential parts: (i) sampling, (ii) designing questions and (iii) interviewing (Fowler, 1993). Only the first two are applicable for a self-distributed questioner like the one used in this research. The sampling has been described in the preceding paragraphs, and we look now at defining the specific questions. The questionnaire has been developed based on the questionnaires used by the reference authors to measure the different factors here evaluated relating to uncertainty and decision-making effectiveness respectively. Following the recommendation and practices of Elbanna and Gherib (2012), the questions have been adapted to the type of business and industry of this research. As described in Chapter 4, the initial 196 factors found in the literature relating to generating uncertainty in decision-making situations, have been finally grouped into 53 factors relating to shipping and ship design. The objective is to facilitate the understanding and readability of the questionnaire while maintaining the reliability of the factors supported by relatively high Cronbach's alpha values achieved in studies from other research fields (α.>=.700).

There are three general principles an effective survey instrument should include: cleanliness, attractiveness, and simplicity (Fowler, 1993). Cleanliness relates to the understanding of the questions, the context in which they should be answered and the connection with the respondent. It is important to communicate to the respondent what the goal of our research is, what is our unit of analysis and in which context the questions are placed. This is why we have an introductory paragraph, which function is to situate the reader into the context of the decision-making problem under evaluation; his or her latest newbuilding project. Attractiveness relates to the structure of the questionnaire, the cleanliness of the questions, the font used, colours, etc. Simplicity relates to the effort the respondent should make to answer the survey. Answers of the type checking a box or circling a number require less effort than providing a written answer. This means that the questionnaire has to rely only on closed questions (Fowler, 1993). We have relied on "check a box" type responses, to increase the speed of response, and consequently, increasing the likelihood of respondents to carry out the survey. When designing questions for a self-distributed survey, the researcher has to pay special attention to the reliability of the questions. All the respondents should have the same understanding of the questions in the survey (Fowler, 1993; Fox, Murray and Warm, 2003). It is recommended to avoid incomplete questions since these are typically a source of unreliability in surveys. On the other hand, too detailed questions may increase the complexity and, therefore, reduce the response rate of the survey. An alternative could be to write the optional explanatory text in parenthesis (Fowler, 1993), so the response can use then for clarity when necessary. In our survey instrument, we have made use of explanatory text in parenthesis to make sure all the respondents would understand the questions in the way they were intended.

Initially, it was considered to utilize only factors and questions from existing questionnaires and with statistical support, Cronbach's alpha. Unfortunately, after running a pre-test with an expert group of four participants, it was found that the questions were too ambiguous for the sample of respondents this survey was targeting. In most of the cases, the questions were targeting management in production facilities in countries with relatively weak political stability or they were extracted from medical surveys. Consequently, it was decided to convert the existing questions to a shipping context. To do so, we identified factors relating to uncertainty in ship design and couple them with the original factors relating to each of the specific questions from our original questionnaire.

Further, a pilot test previous to the distribution of the survey initiated the discussion on whether to include or not a “don’t know” option in the answers. Fowler (1993, p. 76) has a deep discussion on this topic, and considering that may not all the respondent are familiarised with all the aspects covered in the survey, it has been decided to include such an option. Fox *et al.* (2003) argue that having a don’t know or decline option will allow for a distinction between that respondent who doesn’t know the answer, of those who haven’t read it or avoided completely.

5. Data analysis and research results

The central premise for this research study is that uncertainty is inherent in ship design decision-making problems and, that it influences negatively the effectiveness of the conceptual ship design process. Thus, this research suggests that ship designers should explore alternatives to handle and reduce such uncertainty in decision-making processes to improve the effectiveness of their daily design tasks. To handle uncertainty in decision-making processes, it is necessary to understand what factors are contributing to the perception of uncertainty. It is the objective of this chapter to measure and estimate the effect of not handling uncertainty properly.

The data analysis procedure that is followed in this study was elaborated in Chapter 4 of this thesis. A survey instrument that was described in detail in Section 4.5 was used to collect the data. The purpose of this analysis is, therefore, to identify and quantify the principal sources of uncertainty influencing conceptual ship design as perceived by ship owning companies.

5.1. Data collection

5.1.1. Survey distribution

For the selection of the sample, we have considered the information available at the *World Register of Ships* (IHS Fairplay, 2018), accounting for 65 000 email addresses. Further, we have disregarded those that were not updated after 01.01.2010, since the likelihood of being out of service was higher, leaving us with 59 917. Furthermore, only ship owners, managers and operators are relevant for our study, which reduces the overall number of emails to 21 202; of which 20 809 were active. When excluding the companies without vessels in operation or under construction, the total number of emails available was 17 669. Finally, excluding repeated emails, the size of the final sample is 16 189 emails. The sample is still too large for practical distribution and particularly follow-up; hence, only a few of the emails from this final sample were used.

Questback was the selected tool for online distribution and carrying out the survey. On the 13th of March, 500 invitations were sent to randomly selected participants among the 16 189 emails available. The emails were automatically sent over the day. It resulted in 22 emails which could not be delivered while 79 participants could not be reached. As a result, 101 additional invitations (accounting for the 22 + 79 non-effective emails) were sent to maintain the level of participants in the 500 range. Among the 101 new participants invited, 28 could not be reached, and 12 emails could not be delivered. Two weeks after the initial invitation, on the 25th of March, a reminder was sent to the participants that didn't initially respond to the survey. This followed the recommendations from the literature (Dillman, 1978; Brett, 2000). We noticed, through additional test emails included in the survey distribution, that in some cases the emails sent were being stored at the *junk* mailbox. This made it more difficult to be reached by the participants. This was advised to the participants in the reminder email, which did not include a link to the survey, as it was suspected that a long link was the cause for the email ending up at the junk mailbox. Two additional responses were received that day. On the 2nd and 9th of

April, two respective reminders were sent to the remaining participants. Further, together with the third reminder on the 9th of April, it was decided to send a new invitation to 500 additional participants. New reminders were sent on 16th April and 23rd of April. On the 23rd of April, and due to the low response rate, it was decided to send 1 000 new invitations, out of which 185 emails could not be reached, and 57 emails could not be delivered. This was followed by a new remind on the 29th of April, and expansion with 1 000 new invitations. A new reminder was sent to the 7th of May together with 300 additional invitations, rising the overall sample to 3 400 email invitations. Two final reminders were sent on the 13th and 28th of May respectively. Table 5-1 includes an overview of key dates relating to the survey distribution. For each date, it is indicated the number of new invitations, together with the emails that could not be delivered or reached. The number of cumulative responses and the number of participants that suspended the survey after initiated is traced. Dates underlines represent days where new participants were invited to the survey. Those dates without underline relate to reminders only.

Table 5-1 Survey distribution and response development.

	13.mar	25.mar	02.apr	09.apr	16.apr	23.apr	30.apr	07.may	13.may	28.may	Total
New invitations	600	0	0	500	0	1 000	1 000	300	0	0	3 400
Not delivered	34	0	0	56	0	57	123	16	6	9	301
Not reached	107	1	0	115	0	185	172	55	3	8	646
Effective invitations	459	458	459	788	788	1 546	2 251	2 480	2 471	2 454	2 454
Responses	1	2	4	5	9	10	12	18	20	24	24
Suspended	4	4	4	4	7	7	12	22	30	30	30
Not responded	454	452	451	779	772	1 529	2 227	2 440	2 421	2 400	2 400

Out of the 3 400 participants selected to the survey (21% of the 16 189 population), 2 454 were effectively invited. Out of the remaining participants, 645 could not be reached and 301 emails could not be delivered. From the effective participants invited to the survey, only 24 finalised it, of which 23 responded to all the questions, representing a 1% return rate. Additionally, 30 participants initiated the survey and responded partially to it. Five of those left it after the general instruction, 20 throughout the first section relating to uncertainty, and five participants left the survey in the demographic information section. The response rate including this group of suspended participants would have doubled the response rate (2%). Further, seven (7) participants informed that their companies were not involved in vessel newbuilding activity, and were, therefore, not able to respond to the survey. One of the participants informed suggesting that “we are exclusively crew managers”, other informed that “As much as we would like to support your research, we regret to inform you that your request for interview cannot be accommodated”, and a third participant indicated that “Thank you for the opportunity to do this, but we are a 60M motor yacht and the specifics of your survey are not applicable to us or the vessel”.

5.1.2. Response rate

The number of participants in the survey and the selected sample had to be adjusted based on the margin of error and the desired confidence level of the responses. The sample size was calculated based on the population size, the margin of error and the z-score, a representation of the confidence level. The effective population of our study (N) is of 2 454 participants. Hence, with a margin error (e) of 15%, we can achieve a confidence level of 85% with our sample size of 23 participants. This is, however, slightly below the minimum level recommended of 5:1 with respect to the number of independent variables. Thus, the generalization of results becomes questionable, and the statistical power of the regression will be negatively influenced (Hair *et al.*, 2010).

5.1.3. Respondents demographic profile and information

Demographic information was used as a control variable in this research model and work, as previously indicated in Chapter 3. One of the important aspects to consider when evaluating uncertainty perception is the working experience of the respondents, and more specifically, the working experience in ship-related industries. As shown in Section 2.2.5, some researchers like Kruger and Dunning (1999) indicate that experience has an effect on the perception of uncertainty. Figure 5-1 includes an overview of the distribution of the survey participants in terms of working experience (left) and working experience in ship-related industries (right). The majority of the respondents to the survey, 17 (74%) were people with more than 20 years of experience in the ship design industry, and consequently, more than 20 years of experience overall. Further, 4 participants had a working experience of 11 to 20 years, with one of them having less than 10 years in ship-related industries.

Age and gender, which are common demographic factors in survey instruments were explicitly excluded as they are considered as non-relevant for the study in question. We are not aware of research that indicates major deviations in the perception of uncertainty or decision-making effectiveness based on the gender or the age of the participants. Age is, however, indirectly catered for by the experience factor. Some examples from medical research also show that there are no significant differences between male or female in terms of tolerance for ambiguity or stress from uncertainty (Iannello *et al.*, 2017).

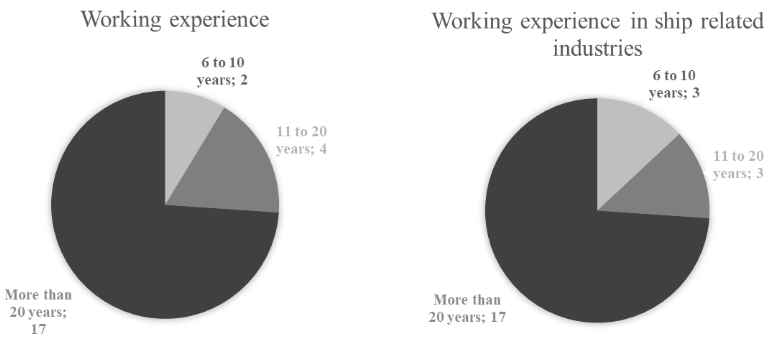


Figure 5-1 Working experience of participants in the survey.

The effect of experience in the response of the participants is explored in Figure 5-2. Experience is here measured as the number of years of experience in ship-related industries. No major differences are found among participants of different groups of experience, although participants with intermediate experience (11 to 20 years) have, on average, lower scores on questions relating to uncertainty, and higher in questions relating to decision-making effectiveness as compared to both, more and less experienced respondents. Less experienced participants scored substantially lower in terms of decision-making effectiveness, as reflects the graph on the right of Figure 5-2.

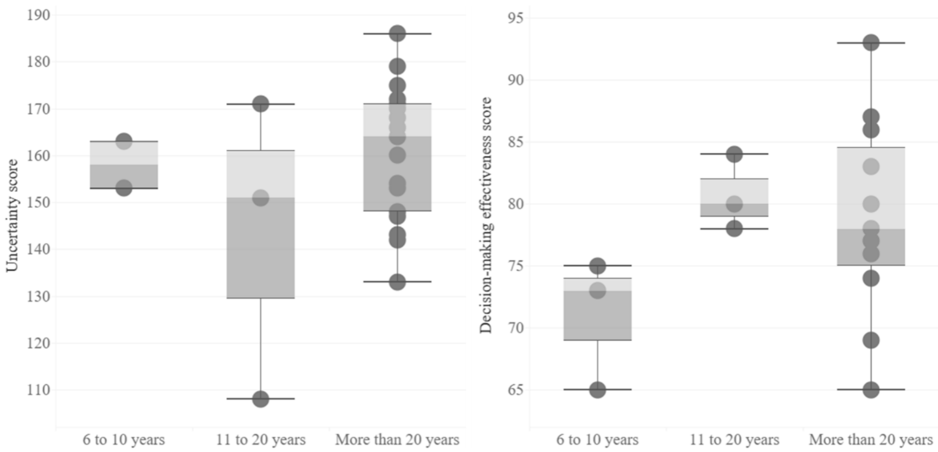


Figure 5-2 Different uncertainty and decision-making effectiveness perceptions by years of experience.

During their years of experience in ship-related industries, the participants of the survey have been involved at different levels on vessel newbuilding projects. Nine (9) of the participants have been involved in ten or more projects before the project used as a reference to this survey. Further, ten (10) participants had experience from at least three projects, three (3) with one or two newbuilding projects and one (1) participant did not have experience with newbuilding projects before the project used as a reference for the survey. Figure 5-3 includes a distribution of the vessel newbuilding experience of the participants in the survey.

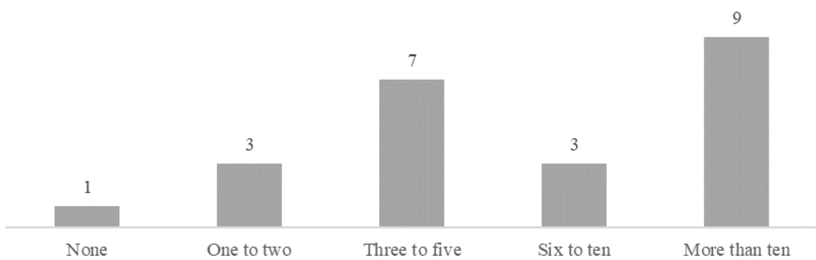


Figure 5-3 Project experience of participants in the survey.

The effect of experience with newbuilding projects is explored in Figure 5-4. Higher deviations are found here. Generally, the perception of uncertainty decreases as participants gain experience. However, the uncertainty perceived by inexperienced participants was substantially lower. This behaviour is in line with what Kruger and Dunning (1999) found on their study and discussed in Section 2.2.5 of this thesis. The differences in terms of the perception of decision-making effectiveness are lower, but in general, the perception increases together with experience.

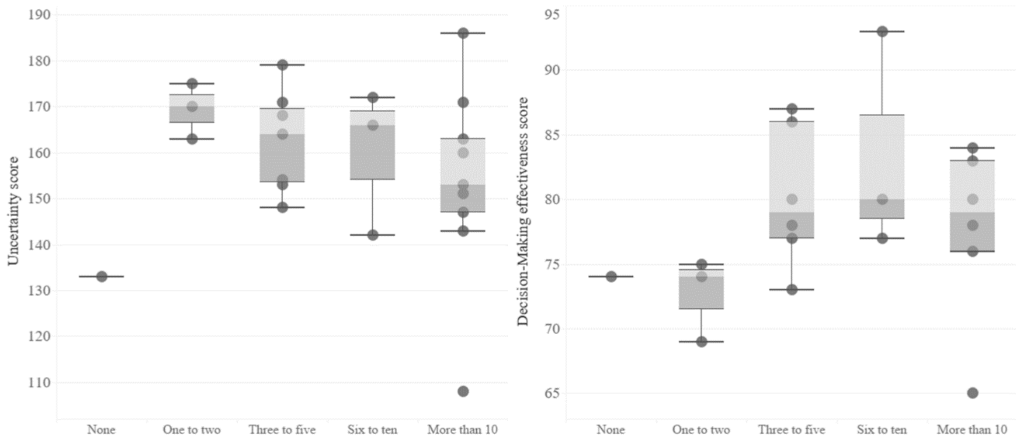


Figure 5-4 Different uncertainty and decision-making effectiveness perceptions by project experience.

The survey instrument does also request the background of the participants in the survey. Thirteen of the 23 participants had an engineering background. One additional participant selected "other background" to concretize his background on naval architecture. Three of the participants with a background in engineering selected also business. The second-largest group of participants were captains or chief engineers, with a total of 10 participants. One of these 10 participants selected also business. Hence, all the participants had a technical background, either engineering, naval architecture or captain/chief engineering. Five of them had, in addition, business background, and one has an economic background. Independently of their background, most of the participants were involved in the projects as technical managers (8), newbuilding manager (5) or project manager (2). Ten additional participants were involved with "other" roles, including one vessel owner, one ship operator, one managing director, one chartering, one consultant and one adviser.

In addition to assessing the background information of the participants, the survey did also request information regarding the projects used as a reference when responding to the survey. The survey participants were asked to respond to the survey considering the last vessel newbuilding project they had been involved with. Most of the projects, ten, were related to merchant vessels, one of them being a chemical tanker and another an oil tanker. Additionally, the projects used as a reference for the survey include three offshore vessels, one fishing vessel and nine vessels of "other type", of which one was a patrol vessel. This is not a surprise considering that the survey sample was chosen randomly among available contact details for shipping companies worldwide. No major differences were found among the participants relating to the type of vessel on their newbuilding projects.

Of the newbuilding projects used as a reference in the survey, nine of them were designed and built together with the customer (end-user) for a specific market segment and region. Other eight projects were designed and built for a specific market segment and region, although in this case, the customer or final user was not involved. Further, three projects were designed and built together with a customer but without a particular project or contract ahead, and another two were built in speculation. One additional project followed a special newbuilding project model since it was relating to a patrol vessel. No major differences were found in the perception of uncertainty among the respondents depending on the newbuilding project model. Some differences were, however, found among their perception of decision-making effectiveness. Projects involving an end-user were perceived by the respondents as more effective than those without the involvement of an end-user. The involvement of the end-user did not increase the perception of decision-making effectiveness in those projects where the vessel was not designed for a specific region and market.

With regards to the operational strategy of the vessel after delivery, most of the projects, seventeen, related to vessels built to be managed and operated by the company of the surveyee. Ten of those were also owned by the company, but the other seven were owned by a third party, therefore, on a bareboat by the company of the surveyee. Further, one vessel was built by a third party and operated on a time charter contract, and one more vessel to be chartered in on a bareboat contract. Finally, two additional projects related to vessels being built to be sold after delivery. The operational strategy has some effects on the perception of uncertainty among the participants in the survey. Uncertainty is perceived the highest when the vessel was designed to be owned, managed and operated by the company of the respondent, and lower when the vessel was built to be sold after delivery. This is a typical risk aversion behaviour. If something goes wrong in the first case, the company has full responsibility and dependency on the vessel, while in the second case, the company will return to a risk-free position when it sells the vessel at its delivery.

5.2. Examination of measurement instrument and data collected

The statistical software SPSS (*Statistical Package for the Social Sciences*) has been used as the basis for the analysis. This software package is included in NTNU's toolbox and is well recognised in academia for statistical analyses.

There are two aspects that have to be considered when analysing the data resulting from a survey: validity and reliability of the measures (Leedy and Ormrod, 2015). Both validity and reliability will judge the extent to which we can learn something from the phenomenon under investigation, and the extent to which we can draw meaningful conclusions from the data (Leedy and Ormrod, 2015). Validity represents the degree to which a measure represents what it is intended to (Denzin, 2009; Hair *et al.*, 2010). Further to validity, it is necessary to measure the reliability of the measures, in other words, the consistency of measurement as opposed to error (Hair *et al.*, 2010).

Additionally, and considering that a multiple linear regression analysis has been used as bases in this study it is necessary to carry out a series of test to ensure that the set of assumptions taken when using this type of analysis in SPSS are satisfied. Eight are the assumptions that should be fulfilled in order to use multivariate: (i) there is one dependent variable and it is measured on a continuous scale; (ii) there are two or more independent variables, they can be measured in continuous or ordinal scales; (iii) independence of observations; (iv) there should be a linear relationship between the dependent variable and each of the independent variables, as well as with all the independent variables collectively; (v) data homoscedasticity; (vi) data should not present collinearity or multicollinearity; (vii) there are no significant outliers, high leverage points or highly influential points; and (viii) all the variables are normally distributed. These eight assumptions are tested and verified in the sections below, before the testing of the research hypotheses.

5.2.1. Reliability testing

The literature identifies three types of consistencies: (a) test-retest reliability or over time reliability, (b) internal consistency across items and (c) consistency across different researchers or inter-rater reliability (Price, Jhangiani and Chiang, 2015). Test-retest reliability relies on the repetition of a specific analysis after a given time of period using the same measurement instrument and to the same group of participants. Having the two samples of data, the Pearson's r score will represent the correlation among them, resulting in good reliability for scores of .80 and above (Price, Jhangiani and Chiang, 2015). This reliability is, however, not of relevance in this case study, since there are no other samples of data to contrast with. For assessing the internal consistency among items, the literature recommends using the coefficient alpha (Cronbach's α), which results directly from the assumptions of the domain sampling model (Churchill and Peter, 1984; Brett, 2000; Denzin, 2009). This alpha coefficient represents the level of acceptable significance or reliability (Hair *et al.*, 2010). The acceptable level of internal reliability for the measurement instrument depends on what the instrument will be used to measure (Brett, 2000; Leedy and Ormrod, 2015), although as a general term, reliabilities of .70 or higher will suffice (Nunnally and Bernstein, 1994; Panayides, 2013). Some authors claim that alpha values should be .80 or higher (Price, Jhangiani and Chiang, 2015), while others suggest that reliability levels of .50 and .60 could suffice (Hair *et al.*, 2010). For situations where important decisions have to be taken, Nunally (1978) recommends alpha levels between .90 and .95. In any case, it is important to ensure that the high coefficient alpha score obtained is not simply the result of the instrument having a large number of items (Panayides, 2013). Hence, in some situations, alpha levels above .70 may reflect too narrow scales (Kline, 1979). The last consistency type is inter-rater reliability, that measures the extent to which different observers make consistent judgments. This reliability is assessed using Cronbach's α for quantitative analyses and Cohen's κ for categorical data (Price, Jhangiani and Chiang, 2015). Further, there exists an alternative to Cronbach's α named Spearman-Brown coefficient. This coefficient is equivalent to the standardized coefficient alpha, and in two-item scales represents, in most of the cases, a less-biased measurement (Eisinga, Grotenhuis and Pelzer, 2013). For the purpose of this analysis, we will use a Cronbach's alpha level of .70 as bases to judge the reliability of the variables.

We start by assessing the internal consistency of the constructs. A Cronbach's alpha analysis was conducted on the independent variable *context* of the uncertainty survey. It was found that the variable's alpha level was .707, which indicates that the variable has an adequate level of inter-item reliability. Further analysis found that deleting the item "competitors" would increase the alpha level up to .722. It could be argued that the Alpha level achieved is a result of the high number of items included in the *context* uncertainty factor (Panayides, 2013). However, the level achieved for *context* with 16 items is equivalent the levels achieved with the other independent variables relating to uncertainty which are described by 4 to 7 items. Hence, it is, therefore, considered that the level achieved by the independent variable *context* cannot be only the result of a larger number of items. A summary of the statistics from the factors part of the independent variable *context* is included in Table 5-2.

Table 5-2 Summary of statistics from factors part of the independent variable context.

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Competitors	57.78	73.723	.006	.722
Regulations	56.30	76.585	-.190	.720
Vessel dayrates (revenue)	56.83	66.514	.259	.700
Market dynamism	57.43	65.530	.324	.691
Vessel costs (excl. fuel)	56.74	69.020	.418	.688
Fuel prices	57.04	68.043	.314	.693
Future vessel requirements	56.57	68.984	.377	.690
Financial factors	56.57	69.802	.256	.698
Institutions (flag state, eg.)	57.22	69.451	.167	.710
Political constrains	58.35	71.419	.105	.714
Market conditions	57.13	64.937	.367	.686
Tax policies	58.09	63.992	.430	.678
Vessel demand	56.70	61.312	.674	.654
Vessel supply	57.00	64.091	.485	.674
Disasters (wars, terrorism, epidemics)	58.87	68.755	.230	.701
Changes in vessel's performance	57.43	68.893	.220	.703
Sea state (waves, wind, current)	57.17	61.332	.494	.669

Similarly, Cronbach's alpha analyses were conducted to the remaining four independent variables (*agent*, *input*, *process* and *model*) and the four dependent variables (*decision rationality*, *decentralization*, *experience* and *intuition*). When analysing the dependent factor *decentralization*, it was found that its alpha level was negative, indicating that some of the questions could have been perceived the opposite way they were intended to. Exploring the item correlation, both the delegation of decision-making and consensus reflect a negative correlation with the two other items in that factor. This was an indication that either the first two items or the latter two should be reversed. Thus, questions relating to item 1 and 2 of the *decentralization* factor were reversed accordingly.

A summary of the Cronbach's alpha levels for the different dependent variable items and independent variables is presented in Table 5-3. Both, the original scale and the adjusted scale are presented. Only one of the nine factors does not have an adequate level of inter-item reliability, with a Cronbach's alpha of .450 after adjustment. Furthermore, six factors have alpha levels above .700, hence adequate according to Nunnally and Bernstein (1994) and Panayides (2013). Additionally, two factors have alpha levels above .600, which according to Hair (2010), are sufficient to prove inter-item reliability.

Table 5-3 Cronbach's alpha for the dependent and independent variables.

Scales' name	Original scale's characteristics:	Adjusted scale's characteristics:	Original no. Items (Adjusted no. Items)
Independent variable: Uncertainty			
Context	.707	.722	17 (16)
Input	.595	.626	5 (4)
Model	.661	.702	7 (6)
Process	.693	.729	7 (6)
Agent	.664	.721	7 (6)
Dependent variable: Effectiveness			
Rationality	.678	.771	5 (4)
Experience	.680	.680	5 (5)
Decentralization	.432	.450	4 (3)
Intuition	.822	.829	6 (6)

Based on the results obtained from the reliability analysis, the investigative model has been adjusted accordingly, eliminating items and factors with low Cronbach's alpha (lower than .600). The new investigative model consists therefore of five independent factors with 38 items, and three dependent factors with 15 items. An overview of the items and factors included in the initial model is presented in Table 5-4 and Table 5-5. Those items and factors excluded in the adjusted model are strike-through in Table 5-4 and Table 5-5. Adjusted constructs and factors are indicated hereafter by a *2* at the end of the name. From here on, all the analyses use the adjusted variables.

The reliability values or Cronbach's Alpha levels found in our study are comparable to those of previous studies with the exception of those obtained for the factor decentralization. The value obtained for decision rationality (.771) is in line with values from previous literature (Dean and Sharfman, 1996; Ji and Dimitratos, 2013; AlDhean, 2017) of .800, .770 and .840 respectively. With respect to experience (.680), is comparable to the .700 found by Ji and Dimitratos (2013); and for intuition (.829), with the value of .780 in AlDhean's work (2017). However, our reliability level found on the decentralization factor (.450) is not in line with the values found from previous literature. Ji and Dimitratos (2013) achieved reliability of .740 and AlDhean (2017) of .750.

Table 5-4 Factors and items included in the initial and adjusted investigative models – independent construct uncertainty in ship design.

Factors	Mean	Std. Deviation	Items
Context	3.040	1.147	~~Competitors~~
	4.520	.511	Regulations
	4.000	1.508	Vessel dayrates (revenue)
	3.390	1.438	Market dynamism (changes in the market)
	4.090	.793	Vessel costs (excl. fuel)
	3.780	1.126	Fuel prices
	4.260	.864	Future vessel requirements
	4.260	1.010	Financial factors
	3.610	1.373	Institutions (flag state, eg.)
	2.480	1.238	Political constraints
	3.700	1.396	Market conditions (at the time of signing the newbuilding contract)
	2.740	1.356	Tax policies
	4.130	1.180	Vessel demand
	3.830	1.230	Vessel supply
	1.960	1.261	Disasters (wars, terrorism, epidemics)
	3.390	1.270	Changes in vessel's performance
	3.650	1.496	Sea state (waves, wind, current)
Agent	3.570	1.121	~~Beliefs (your own beliefs)~~
	3.960	1.022	Communication (with other stakeholders)
	4.390	.722	Experience (your experience with vessel newbuilding projects)
	3.350	1.301	Presence of multiple stakeholders
	3.570	1.343	Relationship between the stakeholders (is it the first project in common?)
	3.480	.947	Skills of the different stakeholders involved in the project
	3.170	.984	Tolerance to ambiguity (your own tolerance)
Input	4.130	.815	Clarity of project scope
	3.430	1.237	Lack of information (regarding the needs of the project)
	4.170	.984	~~Operating strategy (for that specific vessel)~~
	3.740	1.251	Reliability of information
	4.260	.689	Operational region (where the vessel will operate)
Model	3.910	.793	~~Complexity of the vessel design solution~~
	4.170	.937	Calculation of vessel capacities and capabilities
	3.390	1.158	Tolerances
	3.700	.822	Estimates
	4.300	1.063	Economic performance
	3.220	1.536	Lack of understanding of the vessel design solution
	4.090	.996	Operational performance (reliability)
Process	3.430	1.121	Technological innovation
	3.650	1.335	Failure (errors)
	4.260	.752	Goodness of fit (how does the design solution satisfy your expectations)
	3.000	1.348	Lack of knowledge of the process
	3.390	1.644	Lack of knowledge on causal relationships
	3.570	1.472	Vessel design changes (after newbuilding contract)
	4.130	.920	~~Shipbuilding time~~

Table 5-5 Factors and items included in the initial and adjusted investigative models – dependent construct decision-making effectiveness.

Factors	Mean	Std. Deviation	Items
Decision rationality	4.520	.511	Have you looked for specific information before making a decision?
	4.610	.583	Have you analysed specific information before making a decision?
	4.000	1.168	Were quantitative analytics techniques important in making the decision?
	3.780	1.126	~~Have you focused attention on crucial information ignoring other irrelevant information?~~
	4.130	1.014	How important are analytics in the decision-making process?
~~*Decentralization*~~	2.570	.728	~~To what extent have you delegated decision-making in this project?~~
	1.700	.635	~~To what extent have you tried to reach consensus between the decision group members?~~
	4.000	.953	~~To what extent could you control the decision-making process?~~
	4.090	1.041	~~Is the structure of your company characterised by few hierarchical levels in decision-making?~~
Experience	4.300	1.020	To what extent was your company familiarized with the operational region?
	4.300	1.063	To what extent was your company familiarized with the vessel segment?
	3.570	.992	To what extent had your company collaborations (partnerships) in the region?
	4.170	.937	To what extent was your company present in the market?
	3.390	1.076	To what extent had your company collaborations (partnerships) in the vessel segment?
Intuition	3.740	1.010	To what extent did decision-making rely on personal judgment?
	4.220	.600	~~How much emphasis was placed on past experience from a similar decision when making situation?~~
	3.570	.945	To what extent did decision-makers trust their intuition?
	3.130	.815	To what extent did decision-making rely on gut feeling?
	2.960	.825	How much emphasis was placed on intuition as a useful decision-making tool?
	3,430	.945	To what extent did you trust in your intuition?

5.2.2. Validity testing

Reliability is a necessary, but not a sufficient condition for ensuring the validity of a measure (Churchill and Iacobucci, 2010; Price, Jhangiani and Chiang, 2015). A good example is the work of Messerli (2012), who identifies a significant linear correlation ($r = .791$, $P < 0.0001$) between chocolate consumption per capita and Nobel laureates. Yet, a high linear correlation does not imply the validity of the results, since it is not expected that chocolate consumption can have any effect on the likelihood of winning the Nobel prize. Hence, further to the reliability, literature provides a set of principles to judge the validity of the measurement, named: face validity, content validity and criterion validity (Price, Jhangiani and Chiang, 2015). The first principle, face validity, represents the intuition of what appears to be correct. Due to the subjectivity of its interpretation, face validity is considered, at best, very weak evidence of validity (Price, Jhangiani and Chiang, 2015). Yet, it can be a good reference in cases like chocolate consumption and Nobel prize winners. Our first impression will be that chocolate consumption will not predict Nobel results, hence, that test had low face validity. Context validity represents the extent to which a measure covers the construct of interest, in other words, if all the aspects of a construct are covered in the measurement. Finally, criterion validity assesses the correlation of the measure with a variable that is expected to be correlated with. One variant of criterion validity is the so-called discriminant validity. This criterion shares the principles of criterion validity, but rather than using criteria with high correlation with the measure, a criterion with no expected correlation, conceptually distinct, is used.

Initially, and supported by our literature review work, we expect that uncertainty will contribute to decision-making effectiveness. Hence, the face validity test is validated. To further assess the validity of our survey instrument, we ran a pre-test with an expert group to evaluate the overall validity of our survey instrument. The objective of this pre-test was to validate that all the participants had interpreted the questions of the survey instrument in the same way. Context validity is ensured by specifying the context of the survey. In this case, the surveyee is asked to respond to the different questions keeping in mind his or her latest vessel newbuilding project. Further, all the questions have been adapted to the maritime environment, so the participants in the survey could relate to maritime jargon. An example is the use of the words bareboat and time-charter.

5.2.3. Normality testing

It is recommended to have normally distributed data in order to run a multivariate regression analysis. This is especially important in small data samples, such as 30 or fewer observations (Ghasemi and Zahediasl, 2012). If the variation from the normal distribution is sufficiently large, all the resulting statistical tests may be invalid, since multivariate methods assume multivariate normality (Brett, 2000; Hair *et al.*, 2010). The more concentrated the data around the point of central tendency, the higher the probability of correctly selecting where the data point lies (Leedy and Ormrod, 2015).

Firstly, we run a summary of descriptive statistic functions for both, dependent and independent variables. These descriptive statistics include, among others: mean, median, variance, standard deviation, minimum and maximum. This information is summarized in appendix C. The Skewness and Kurtosis ratios are also included and will be used in the evaluation of normality later in this section. Further, we run the normality check with SPSS based on both, the Kolmogorov-Smirnov and the Shapiro-Wilk tests. Both tests result in different interpretations of normality, but in general, they target different sample sizes. For small sample sizes of less than 50 observations, the Shapiro-Wilk test is recommended (Shapiro and Wilk, 1965; Shapiro, Wilk and Chen, 1968). The Kolmogorov-Smirnov test, also known as the K-S test, is better fitted for medium to large samples. According to Howell (2010), the K-S test in small samples will reflect normality even if the sample is no-normal, while for very large samples, the test will reject the hypothesis of normality even for minor deviations of normality. In general, the K-S test is not recommended for use (D'Agostino and Stephens, 1986; Howell, 2010; Ghasemi and Zahediasl, 2012). Hence, although we run both tests on SPSS, we used the Shapiro-Wilk test as a reference to evaluate the normality of the items in our sample. Further, the literature recommends to not rely only on these two parameters, but additionally have a look at the data itself and its distribution. As a consequence, we evaluate the distribution of the items by means of graphical representation; see graphs in appendix D.

Based on our sample size, if the statistic value (z) exceeds the values -1.96 or 1.96, or the significance level (p) is below .050 the hypothesis of normality can be rejected (Brett, 2000; Ghasemi and Zahediasl, 2012). Table 5-6 includes an overview of the statistic values (z) and significance levels (p) for all the items studied, both, based on the Kolmogorov-Smirnov test (including Lilliefors significance correction), and the Shapiro-Wilk test. None of the factors or constructs exhibits statistical significance departure from normality in terms of their statistic value (z), however, they do in terms of their significance (p). Considering the significance levels (p), two factors differ from normality based on the Shapiro-Wilk test, *context* and *experience*. If we explore the histogram and the normal Q-Q plots from appendix D for the factor context, we can see that it is slightly left-skewed. The factor experience is slightly non-peaked, with extreme values in the centre and both extremes.

Table 5-6 Normality test of dependent and independent variables.

	df	Skewness	Kurtosis	Kolmogorov-Smirnov[a]		Shapiro-Wilk		Description
				Statistic (z)	Sig. (p)	Statistic (z)	Sig. (p)	
Context2	23	-1.009	.044	.209	.011	.877	.009	Non-normal
Agent2	23	-.143	-1.017	.127	.200*	.961	.483	Normal
Input2	23	-.466	-.154	.170	.084	.940	.184	Normal
Model2	23	-.787	1.509	.161	.126	.931	.116	Normal
Process2	23	.390	.735	.196	.022	.957	.404	Normal
DMrationality2	23	-.606	-.807	.178	.058	.875	.008	Normal
Experience2	23	-.616	1.036	.173	.074	.913	.046	Non-normal
Intuition2	23	.531	-.717	.158	.141	.918	.059	Normal

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

The values for Skewness and Kurtosis give also an indication of the shape of the distribution. Skewness relates to the symmetry of the distribution. Hence, the distribution is fairly symmetrical for Skewness values between -.500 and .500. For values above .500 or below -.500, the data is moderately skewed, positively skewed and negatively skewed respectively. On the other hand, Kurtosis relates to the height and sharpness of the central peak of the distribution. In this respect, the more highly peaked the data, the more encouraging its estimates of empirical fit, however, this advantage may be misleading (Olsson *et al.*, 2000).

Kaplan (1990) suggests that Skewness and Kurtosis values lower than 1.0 are preferable in normality evaluations. All the factors, with the exception of one (*context*), have a Skewness value lower than 1.0 or higher than -1.0. *Context* has a Skewness value marginally larger than 1.0. Three factors have Kustoris values larger than 1.0. For *agent* and *experience*, the Kurtosis values are slightly superior to 1.0; but for *model*, this value is substantially higher, see Table 5-6. However, Olsson *et al.* (2000) suggest that values higher than this may be acceptable, and Gravetter and Wallnau (2014) assume normality within the range (-2,2) for Kurtosis. Thus, it has not been considered necessary to introduce any remedies for non-normality of factors' data in this study.

5.2.4. Homoscedasticity and heteroscedasticity testing

Heteroscedasticity reflects the presence of unequal variances and is one of the most common assumption violations in linear regression analysis (Hair *et al.*, 2010). One simple way for the diagnosis of heteroscedasticity or contrary homoscedasticity (equal variances) is by plotting the standardized residuals against the predicted dependent variable, as shown in Figure 5-5. From a visual inspection of the graph in Figure 5-5, no major deviations are perceived on the variance of error along with the values for the dependent variable. Thus, the data reflects homoscedasticity.

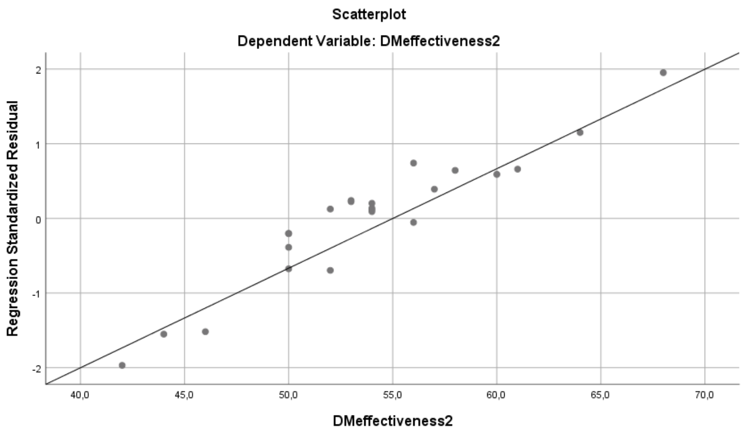


Figure 5-5 Homoscedasticity – heteroscedasticity test.

5.2.5. Examining relationships among variables

As a complement to the examination of the distribution of single variables, the relationship between two or more variables is critical for multivariate analyses (Brett, 2000). Our original survey instrument with nine predictor variables, five for uncertainty and four for decision-making effectiveness, consisted of 63 items out of which, eleven were discriminated for weak consistency. Yet, there is a danger that a large number of items in the adjusted measurement instrument (52 in this analysis) is increasing the statistical fit of the data at the expense of over-fitting data and making less generalisable to the population (Hair *et al.*, 2010). One of these elements is multi-collinearity.

Collinearity and multi-collinearity cause redundant information, as it reflects the degree to which other variables can predict the effect of a given variable (Hair *et al.*, 2010). Inaccuracy resulting from collinearity can distort the interpretation of the model, and increase the risk of false-positive results (Type I error) and false-negative results (Type II error) (Yoo *et al.*, 2014). There are multiple suggestions for diagnosing the presence of collinearity in models. One of these techniques is an examination of the correlation matrix for dependent and independent variables. The presence of high correlation is the first indicator of collinearity. Hair *et al.* (2010) suggest that correlation values above 0.9 should be further investigated as potential indications of collinearity. The inter-item collinearity matrix for dependent and independent variables is presented in Table 5-7.

Table 5-7 Inter-item collinearity of dependent and independent variables.

	Context2	*Agent2*	*Input2*	*Model2*	*Process2*	*DMrationality2*	*Intuition2*	*Experience2*
Context2	1							
Agent2	.068	1						
Input2	.204	.557**	1					
Model2	.341	.295	.537**	1				
Process2	.389	-.159	.229	.478*	1			
DMrationality2						1		
Intuition2						.074	1	
Experience2						.068	.115	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Out of the sixteen correlations shown in Table 5-7, only three show a significant correlation. Most of the variables show a positive correlation, although there is one negative correlation, between the factors *process* and *agent* part of the uncertainty construct. The range of correlations varies from -.177 to .557. Thus, in any case, correlations surpass the limit of .900 suggested by Hair *et al*. (2010) and Yoo *et al.* (2014) or the limit of .700 suggested by Dormann *et al.* (2013). Hence, none of the dependent or independent variables in this study is suspect of bivariate collinearity.

Testing multicollinearity was also carried out. In this case, we studied the relationship between more than two independent variables to identify if one of the variables is a linear combination of the other variables. The variance important factors (VIF) is one of the most extended rules (Yoo *et al.*, 2014). The VIF indicates the strength of the linear dependencies. In general, the literature suggests that VIF values above 10.0 reflect multicollinearity (Dormann *et al.*, 2013; Yoo *et al.*, 2014), and if the values are above 3.0, it is probable that there exists multicollinearity. The tolerance is the amount of independent variable not explained by the other variable. Hence, small tolerances denote high collinearity and indicate that a given variable has little contribution to the model (Brett, 2000). Literature suggests here to consider a threshold of .100 (Hair *et al.*, 2010). The estimated VIF for the independent variables of our study range 1.136 to 1.916 and the tolerances range .522 to .880. Both tolerance and VIF values are inside the thresholds indicated by literature, suggesting that collinearity and multicollinearity should not present data problems in this research. All the values for the five independent variables are presented in Table 5-8.

Table 5-8 Tolerance and VIF coefficient for the five independent variables.

Coefficients (*Context2*)

	Tolerance	VIF
Agent2	.586	1.708
Input2	.522	1.916
Model2	.561	1.782
Process2	.654	1.530

Coefficients (*Agent2*)

	Tolerance	VIF
Input2	.710	1.409
Model2	.566	1.767
Process2	.712	1.404
Context2	.816	1.225

Coefficients (*Model2*)

	Tolerance	VIF
Input2	.585	1.709
Process2	.719	1.391
Context2	.829	1.206
Agent2	.600	1.667

Coefficients (*Input2*)

	Tolerance	VIF
Process2	.621	1.611
Context2	.814	1.229
Agent2	.793	1.260
Model2	.617	1.620

Coefficients (*Process2*)

	Tolerance	VIF
Context2	.880	1.136
Agent2	.688	1.453
Model2	.656	1.525
Input2	.536	1.864

5.3. Evaluation of the research model

Multiple linear regression analysis has been used as bases in this study to evaluate the relationship between the single dependent variable and the five independent predictor variables. The objective of this study is to use the independent predictor variables, known from this study, to predict the single dependent variable and, at the same time, the changes in the dependent variable in response to changes in the independent predictor variables. The coefficient of determination (R^2), calculated as the squared correlation between the dependent variable and the independent variables (plus intercept), is the most popular measure for assessing the accuracy of the regression model (Hair *et al.*, 2010). Thus, R^2 represents the amount of variance in the dependent variable explained by the independent predictor variables. Its value ranges from .000 (no prediction) to 1.000 (perfect prediction). A more conservative approach is considering the adjusted R^2, which takes into consideration the number of independent variables and the number of observations (responses) (Brett, 2000). Further, the F-ratio resulting from the analysis tests the fit of the regression model to the data. This ratio allows the testing of the null hypothesis (Bryman and Cramer, 1999).

Before we proceed further with the testing of the hypothesis, we will review the set of assumptions that have to be satisfied before using multivariate regression analysis. From our research model and the survey instrument, we can corroborate that our data include one dependent variable on a continues to scale, and five independent variables, thus, assumptions (i) and (iii) (see Section 5.2) are fulfilled. The test for independence of observations is commonly assessed by the *Durbin-Watson* test (DW). This is carried out together with the multi-variate regression analysis and presented in Table 5-9. The value of DW for our data is of 1.833, which indicates a low level of autocorrelation. A DW equal to 2.0 indicates no autocorrelation, while a DW of 0.0 indicates a perfect negative autocorrelation and DW = 4.0 a perfect positive autocorrelation. Some sources suggest that this test is, however, irrelevant when analysing survey data that is time-independent. The linearity assumption (iv) is explored by means of graphical representation. Appendix E includes the scatterplot matrix for the 5-predictor variables individually and in conjunction, together with the dependent variable decision-making effectiveness. The homoscedasticity of the data was proven in Section 5.2.4 of this chapter, thus assumption (v) is also satisfied. Similarly, the study of collinearity and multicollinearity was carried out in Section 5.2.5, excluding the presence of collinearity or multicollinearity in the data. Finally, the normality of the predictor variables was proven in Section 5.2.3. Thus, all the assumptions for carrying out multivariate regression analysis are satisfied, and we can proceed further with the analysis and the testing of the hypotheses.

Based on the literature review and theorization work carried out in the previous chapters of this thesis, five, a priori, content characteristics of uncertainty in conceptual ship design were identified. For each of these five content characteristics, one research hypothesis was formulated. All of the five hypotheses suggest that uncertainty influence decision-making effectiveness in conceptual ship design. Further, one additional hypothesis was also proposed inverted from theory propositions and tested in this chapter of the thesis. Firstly, we run a multivariate confirmatory analysis based on the research model proposed in the theorization chapter including the original five independent variables and their corresponding hypothesis H_0; H_{1-5}. Further, we carry out a backward elimination test to explore potential alternative models with higher explanatory power. However, none of the five alternatives explored (eliminating one of the five independent variables at the time) resulted in higher beta coefficients.

5.4. Results from the analysis

Results are presented in Table 5-9, where the first column all variables represent the results from the confirmatory analysis (Model A) and the consecutive columns the five backwards elimination tests excluding one of the independent variables at the time (Models B to F).

Table 5-9 Results from the six regression models studied.

	Model A All variables	*Model B Excl. Context*	*Model C Excl. Agent*	*Model D Excl. Input*	*Model E Excl. Model*	*Model F Excl. Process*
R2	.140	.109	.118	.119	.126	.082
Adjusted R2	-.113	-.089	-.077	-.076	-.069	-.122
Std. error	6.344	6.275	6.240	6.238	6.215	6.369
F ratio	.552	.549	.605	.610	.647	.401
Durbin-Watson	1.791	1.576	1.583	1.566	1.775	1.905

The multiple R for the multiple regression analysis according to the confirmatory analysis (Model A) is .374, and the corresponding coefficient of determination R^2 is .140. None of the five backwards elimination tests resulted in an R^2 above .140, being in the range .082 to .126. The higher value of R^2 for the confirmatory analysis can result from the use of one additional variable as compared to the five alternative models – five independent variables compared to four. The adjusted R^2 accounts for this, and it is, therefore, a better reference to compare regression models. All the adjusted R^2 are negative values. One explanation for the negative values is the low number of observations. Considering Equation 11, where n is the number of observations and p the number of predictor independent variables, with a low value for R^2, the value of adjusted R^2 will result negative. The lowest value is in this case for model E, where the independent variable *model* is excluded.

$$Adj.R^2 = 1 - \left\{\left[\frac{n-1}{n-p-1}\right] \times (1 - R^2)\right\} \qquad \text{Equation 11}$$

However, how accurate the prediction of each regression model is, is still an open question. We can assess the predictive power of the different regressions by the standard error of the estimate (Hair *et al.*, 2010). The backward elimination test where the factor *model* is excluded (Model E) presents the lowest standard error, although the differences are minimal among the six alternative regression models. Further, this model presents the highest F ratio, which reflects the ratio of the explained variance. None of the models shows statistical significance from the ANOVA test. Hence, we proceed further with the results for the regression model resulting from the confirmatory test (Model A). Next, we summarize the results from model E extracted from the backward elimination process by neglecting the factor *model*.

Table 5-10 includes the results from the multivariate regression analysis of Model A. The regression coefficients *b* and *Beta* (columns one and three of Table 5-10 respectively) reflect the change in the dependent variable for each unit change in the five independent factors. Exploring the standardized Beta coefficient, we see that the independent variable *context* has the largest positive contribution to decision-making effectiveness. Further, both *input* and *process* have a negative contribution to the dependent variable decision-making effectiveness.

Table 5-10 Statistical results from the regression analysis of Model A.

	Unstandardized Coefficients		*Standardized Coefficients*	*t*	*Sig.*
	B	*Std. Error*	*Beta*		
(Constant)	48.996	11.943		4.103	.001
Context2	.136	.175	.195	.781	.446
Agent2	.275	.425	.190	.646	.527
Input2	-.419	.663	-.197	-.632	.536
Model2	.227	.443	.159	.524	.607
Process2	-.363	.340	-.309	-1.069	.300

A representation of the investigative Model A with the respective Beta values is presented in Figure 5-6.

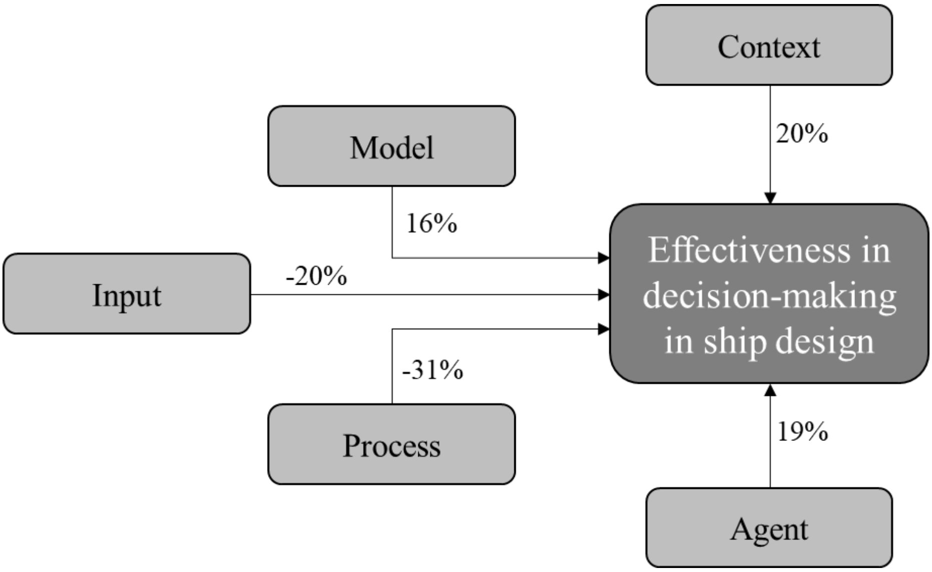


Figure 5-6 Investigative Model A with results (β-values).

Table 5-11 includes the results from the multivariate regression analysis of Model E. The regression coefficients *b* and *Beta* (columns one and three of Table 5-11 respectively) reflect the change in the dependent variable for each unit change in the four independent variables. Exploring the standardized Beta coefficient, we see that the independent variable *agent* has the largest positive contribution to decision-making effectiveness. Further, both *input* and *process* have a negative correlation with the dependent variable.

Table 5-11 *Statistical results from the regression analysis of Model E.*

	Unstandardized Coefficients		*Standardized Coefficients*	*t*	*Sig.*
	B	*Std. Error*	*Beta*		
(Constant)	49.361	11.680		4.226	.001
Context2	.149	.169	.213	.879	.391
Agent2	.311	.411	.216	.758	.458
Input2	-.304	.613	-.143	-.497	.626
Process2	-.292	.305	-.249	-.957	.351

A representation of the investigative Model E with the respective Beta values is presented in Figure 5-7.

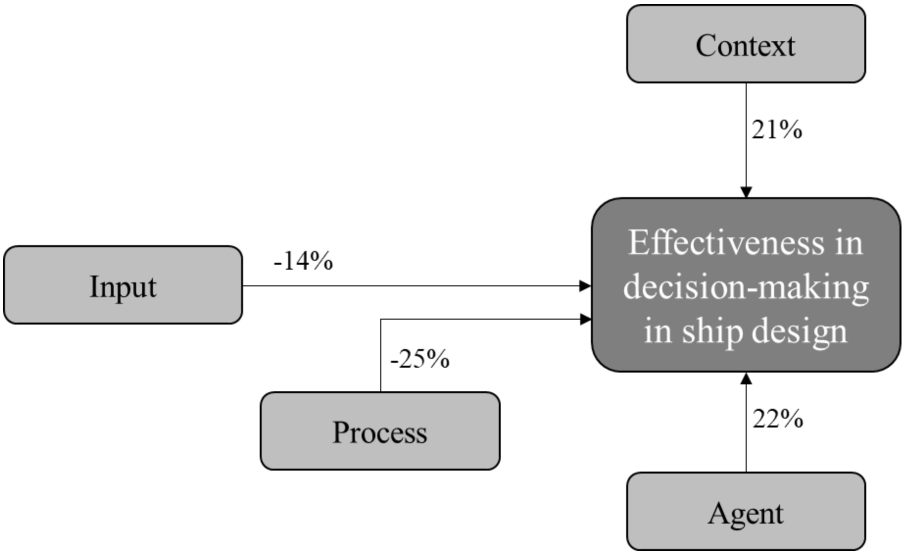


Figure 5-7 Investigative Model E with results (β-values).

These findings and models need to be validated, to ensure the generalizability of the results and the appropriateness of the model to the general population. For this purpose, Hair *et al*. (2010) suggest two alternatives, to run an empirical validation with an additional sample, or a split of the original sample. However, none of these alternatives is relevant to this case. Firstly because of the lack of time to distribute the survey on a new sample, and second because the size of the original sample is already reduced and does not allow for splits. Thus, as an alternative to these two approaches, it has been decided to run a regression analysis based on part of the original sample. Fifteen of the twenty-three original responses were selected randomly and used as a sample for this validation study.

The multiple R for the multiple regression analysis according to the confirmatory analysis (Model A) is .497, and the corresponding coefficient of determination R^2 is .247.

Table 5-12 Statistical results from the regression analysis of Model A for a reduced sample.

	Unstandardized Coefficients		*Standardized Coefficients*	*t*	*Sig.*
	B	*Std. Error*	*Beta*		
(Constant)	37.434	17.649		2.121	.063
Context2	.200	.228	.269	.880	.402
Agent2	.569	.580	.372	.982	.352
Input2	-.674	.879	-.327	-.767	.463
Model2	.397	.544	.253	.730	.484
Process2	-.217	.455	-.184	-.476	.646

5.5. Testing of hypothesis

As bases for testing our research hypotheses, we used the results from the regression model resulting from the confirmatory test (Model A) presented in Section 5.4. The starting point for the hypothesis testing in this research study is the null hypothesis (H_0) which states "There is no positive relationship between low design decision-making uncertainty and effective decision-making in vessel conceptual design processes". Thus, the null hypothesis (H_0) suggests that there is no relationship between the dependent variable and the independent variables. The F ratio test allows for the testing of the null hypothesis that the multiple correlations are zero in the population from which the sample is taken (Bryman and Cramer, 1999). For the selected Model A, the regression equation has an F ratio of .552 with a significance level of .735, suggesting that it is improbable that R will be zero in the population. Hence, the results of this research suggest that there is a relationship between the independent and the dependent construct, although it cannot be confirmed with statistical significance.

The first hypothesis of this research (H_1) claims that a better understanding of decision-making *context* is positively associated with effective decision-making in vessel conceptual design processes. Analysing the responses from the 23 participants in the survey we find that a unitary change in *context* will contribute to a positive change of decision-making effectiveness in the ratio of .195 (19.5%) (Ref. Table 5-10 and Figure 5-8). Yet, H_1 cannot be confirmed with statistical significance.

The second hypothesis of this research (H_2) claims that a better understanding of decision-making *input* is positively associated with effective decision-making in vessel conceptual design processes. Analysing the responses from the 23 participants in the survey we find the opposite effect. For a unitary change in *input*, decision-making effectiveness will decrease a by -.197 (-19.7%) (Ref. Table 5-10 and Figure 5-6). This result is opposite to what literature suggests. Yet, H_2 cannot be rejected with statistical significance.

The third hypothesis of this research (H_3) claims that a better understanding of decision-making *model* is positively associated with effective decision-making in vessel conceptual design processes. Analysing the responses from the survey we find that a unitary change in *model* will contribute to a positive change of decision-making effectiveness with the ratio of .159 (15.9%) (Ref. Table 5-10 and Figure 5-6). Yet, H_3 cannot be confirmed with statistical significance.

The fourth hypothesis of this research (H_4) claims that a better understanding of decision-making *process* is positively associated with effective decision-making in vessel conceptual design processes. Analysing the responses from the 23 participants in the survey we find the opposite effect. For a unitary change in *process*, decision-making effectiveness will decrease by -.309 (-30.9%) (Ref. Table 5-10 and Figure 5-6). This result is opposed to what previous literature suggests. Yet, H_4 cannot be rejected with statistical significance.

The fifth hypothesis of this research (H_5) claims that a better understanding of decision-making *agent* is positively associated with effective decision-making in vessel conceptual design processes. Analysing the responses from the survey we find that a unitary change in *agent* will contribute to a positive change of decision-making effectiveness in the ratio of .190 (19%) (Ref. Table 5-10 and Figure 5-6). Yet, H_5 cannot be confirmed with statistical significance.

An overview of the results relating to the five research hypothesis is presented in Table 5-13.

Table 5-13 Summary of research hypothesis testing based on Model A.

	Research hypothesis	*Results*
H1	Better understanding of decision-making *context* is positively associated with effective decision-making in vessel conceptual design processes.	Not confirmed P = .446 > .100 N = 23
H2	Better understanding of decision-making *input* is positively associated with effective decision-making in vessel conceptual design processes.	Not confirmed P = .527 > .100 N = 23
H3	Better understanding of the decision-making *model* is positively associated with effective decision-making in vessel conceptual design processes.	Not confirmed P = .536 >.100 N = 23
H4	Better understanding of the decision-making *process* is positively associated with effective decision-making in vessel conceptual design processes.	Not confirmed P = .607> .100 N = 23
H5	Better understanding of the decision-making *agent* is positively associated with effective decision-making in vessel conceptual design processes.	Not confirmed P = .300 > .100 N = 23

5.6. Interpretation of results

The objective of this research was to explore how uncertainty affects the effectiveness of decision-making in conceptual ship design processes: does uncertainty in ship design (independent variable) influence the effectiveness in decision-making in ship design (dependent variable)? As part of this research, a research model has been developed to measure both constructs and their relationship, and it has been populated with data via a survey instrument distributed and responded to electronically by ship owners. The research results suggest that the presence of uncertainty in ship design processes can explain 14% of the variability in the effectiveness of the design decision-making process. Yet, no statistical significance has been found to support the findings.

Three of the independent uncertainty factors, *context*, *agent* and *model* have a positive Beta value, indicating that one unit change in the function will produce a positive change of effectiveness of magnitude Beta. On the other hand, the factors *input* and *process* have a negative Beta value. This is actually opposite of what theory suggests they should be. In the paragraphs below I explore these results reflecting how these findings affect contemporary ship design processes.

Exogenous factors affecting the decision-making process, involving design, construction and future operation of the vessel, have the highest positive contribution to decision-making effectiveness. Thus, supporting the findings from Duncan (1972), who suggest that the dynamism of the environment (*context*) has a stronger influence on the perceived uncertainty than the *model* or *process* uncertainty. These results were not unexpected since most of the recent research on ship design under uncertainty has focused on handling environmental uncertainty, as already argued in earlier chapters of this thesis. Yet, in contemporary ship design practices, we normally pay little attention to contextual factors (*context*). In most of the cases, the handling of contextual factors is left to the vessel owner, who defines the set of criteria and expectations for the new vessel design; and in one way or another, convey this to the ship designer. Fidelity and quality are very often lost because of improper transfer and ineffective communication between the owner and the ship designer. Based on the findings from our study, ship designers should, therefore, pay much more attention to the markets they are operating in and guide their customers in how to design better vessels able to handle changes in a given set of market conditions, Regulations, operational requirements or costs, such as fuel.

Unsurprisingly, *agent* is the second factor with the highest positive contribution to decision making-effectiveness. Both *context* and *agent* are argued in the literature as the two largest contributors to uncertainty in decision-making problems (Fantino and Stolarz-Fantino, 2005; Kochenderfer, 2015). This is confirmed by this research study. In a multi-stakeholder activity like ship design, the management of stakeholders is critical for the design process. In some cases, where the customer is represented by more than one stakeholder, the design process can lead to irrational, over-specified design solutions (Garcia *et al.*, 2019). To handle this aspect of complexity and corresponding uncertainty, ship designers need to develop a good relationship with the stakeholders they are working with. Hence, the importance of maintaining a good relationship with existing customers. Group workshops in the early phase of the design process are beneficial and recommended (Brett, Boulougouris, *et al.*, 2006).

Together with *process*, the factor *input* has also a negative contribution to the effectiveness of decision-making processes. This finding contradicts most of the literature on design theory that suggests that *input* is the most important aspect of a design process (Coyne *et al.*, 1990; Suh, 1990). It is unclear to us the reasons behind the perception of a negative effect of *input* in the effectiveness of the decision process. One potential explanation could be the fact that *input* relates to the information provided by the shipowner itself to the designer and is thereby considered given. Thus, he or she will consider the time spent on adjusting the *input* as time loss, thus reducing the effectiveness of the process.

Model is found to have a positive relationship to decision-making effectiveness, although the weakest effect among the three factors showing a positive effect. *Model* reflects the uncertainty on the consequences of design decisions. What will be the cost of having X? or Y? Today, most of the ship design practice relies on using advanced software that although accurate, requires a substantial amount of resources and time to execute the analysis. Hence, designers and vessel owners have to proceed with decisions without fully understanding their consequences and iterate if the output and outcome of their decisions are not as expected. This rework is, by the way, a substantial source of ineffectiveness in ship design processes (Lyon and Mistree, 1985).

Process has the strongest contribution to effectiveness in decision making based on the findings from our model. Yet, its effect is negative, contrary to our initial proposition and what literature suggests. *Process* relates to the uncertainty created during the design process, lack of understanding of the product and how it will fulfil the expectations it was designed for. To a large extent, it relies on the control the ship designer has on the process and the product and is strongly dependent on the degree of innovation and newness of the design solution. A potential reason for the negative influence of *process* in decision-making effectiveness is the role of innovation. Ship design firms may perceive as negative the role of innovation in the design process, although it may have positive effects in the final vessel design solution.

The five independent factors and their associated items contribute to a different degree to the effectiveness of the conceptual ship design process. In spite of the differences in the perception of how the diverse factors contribute to uncertainty in design processes, ship designers do not put effort on them accordingly. Frequently used ship design theories cover asymmetrically the different uncertainty items identified in this research work. As presented in Table 5-14, these theories, typically, focus on only a few, and not necessarily the most important, of all the elements contributing to the perception of uncertainty in ship design processes. Commonly used ship design theories are represented by 29 publications reviewed by Ulstein and Brett (2012), which include most of the recognized ship design theories with their special features. In Table 5-14 we have related the items from the research model to the relating design activities in design theories. Each of the items is companied by its mean value resulting from the response of the 23 participants. The mean value represents the importance of each item as perceived by the ship owning companies on a 1 to 5 scale, where “1 = not influential at all” and “5= extremely influential”. Further, we count the number of appearances of these design activities in the 29 publications reviewed by Ulstein and Brett (2012). Each of the design activities captured by Ulstein and Brett (2012) are associated with commercial (C), technical (T) and operational (O) aspects.

From the review of the information presented in Table 5-14, we can conclude that most ship design theories need to improve in many critical facets and in particular, with respect to how to handle uncertainty to improve the effectiveness of conceptual ship design processes. In spite of its recognised importance identified in our survey instrument, commonly used ship design theories underemphasize the importance of activities like a business proposition, cost-benefit analysis and life-cycle analysis. Better handling of commercial factors such as vessel dayrates, market dynamism, and future vessel requirements or stakeholder expectations, is still a pending issue in ship design theories, although improvements have been done in the latter years. Simulation techniques (Balland *et al.*, 2013), scenario planning and Epoch Era evaluations (Keane, Gaspar and Brett, 2015) or the use of design ilities (Rehn *et al.*, 2019), are some examples of recent theoretical developments in this direction. Similarly, there is little reference to stakeholder behaviour and more generally to the factor *agent* in ship design literature. More recently, ship design researchers and practitioners have proposed collaborative approaches to handle the uncertainty of multiple stakeholders (Brett, Boulougouris, *et al.*, 2006; Chalfant *et al.*, 2012; Garcia *et al.*, 2019). *Input* items, relating to the completeness, reliability and validity of the information confining the vessel business idea are, too often, left aside in ship design practice. The expectations of the vessel owner are taken as requirements and are rarely critically questioned, in spite of its importance (Andrews, 2011).

Table 5-14. Contrast of item importance and ship design effort.

	Questionnaire items	Mean value in the survey	Relating design activities in ship design theories	Perspective (C/T/O)	No.of appearances
Context	Regulations	4.520	Criteria specification	T	28
	Vessel dayrates	4.000	Business proposition	C	6
	Market dynamism	3.390	Business proposition	C	6
	Vessel costs (excl. fuel)	4.090	Cost-benefit analysis	C	12
	Fuel prices	3.780	Life-cycle analysis	C	1
	Future vessel requirements	4.260	Life-cycle analysis	C	1
	Financial factors	4.260	Business proposition	C	6
	Institutions (flag state, eg.)	3.610	Stakeholder expectations	C	15
	Political constrains	2.480	Solution space constraints	C	9
	Market conditions	3.700	Business proposition	C	6
	Tax policies	2.740	Solution space constraints	C	9
	Vessel demand	4.130	Business proposition	C	6
	Vessel supply	3.830	Business proposition	C	6
	Disasters (wars, terrorism, epidemics)	1.960	Risk and reliability analysis	C	4
	Changes in vessel's performance	3.390	Goodness of fit analysis	C	3
	Sea state (waves, wind, current)	3.650	Criteria specification	T	28
Agent	Communication (with other stakeholders)	3.960	Feedback to design	O	5
	Experience	4.390	Training and preparations	O	2
	Presence of multiple stakeholders	3.350	Stakeholder expectations	C	15
	Relationship between the stakeholders	3.570	Stakeholder expectations	C	15
	Skills of the different stakeholders involved in the project	3.480	Risk and reliability analysis	C	4
	Tolerance to ambiguity (your own tolerance)	3.170	Risk and reliability analysis	C	4
Input	Clarity of project scope	4.130	Stakeholder expectations	C	15
	Lack of information (regarding the needs of the project)	3.430	Stakeholder expectations	C	15
	Reliability of information	3.740	Risk and reliability analysis	C	4
	Operational region (where the vessel will operate)	4.260	Business proposition	C	6
Model	Calculation of vessel capacities and capabilities	4.170	Capacity and capability statement	T	28
	Tolerances	3.390	Solution space constraints	C	9
	Estimates	3.700	Parametric analysis; balancing of the design	T	4; 7
	Economic performance	4.300	Performance yield benchmarking	C	3
	Lack of understanding of the vessel design solution	3.220	Systems architecture; balancing of the design	T	24; 7
	Operational performance (reliability)	4.090	Risk and reliability analysis; performance yield benchmarking	C	4; 3
Process	Technological innovation	3.430	Radical ideas and inventions	C	3
	Failure (errors)	3.650	Risk and reliability analysis	C	4
	Goodness of fit	4.260	Goodness of fit analysis	C	3
	Lack of knowledge of the process	3.000	Stakeholder expectations; tendering	C	15; 2
	Lack of knowledge on causal relationships	3.390	Systems architecture; cost-benefit analysis	T	24; 12
	Vessel design changes (after newbuilding contract)	3.570	Life-cycle analysis	C	1

Regulations represent the uncertainty item with the highest importance for shipping companies, based on the response to our survey. However, we couldn't find any reference in the literature or strong indications in theory suggesting this. A potential explanation for this discrepancy could be the current situation of the shipping industry with multiple environmental regulations coming into force on a short period of time. The second item in terms of importance is the experience of the decision-makers with newbuilding projects, and in third place, it is the economic performance of the vessel. Contrary, disasters, political constraints and tax policies are perceived as the items with the lowest importance with respect to uncertainty handling in conceptual ship design processes today.

Thus, knowing this information, ship design practitioners should concentrate their efforts on those factors perceived as more important, and put less emphasis on those with lower relevance. In the current shipping environment, ship design firms shall provide shipping companies with advice on how to manage and comply with future regulations relating to, for example, emissions. There exist multiple alternatives to comply with the new limits of SOx emissions coming into force in 2020. Ship design firms should inform shipping companies about these alternatives, and their consequences and implications for the operation of the vessel. We, ship designers, have to play a more active role in such decision-making situations than in the past. This aspect also relates to the economic performance of the vessel business case. The experience of the shipping company with newbuilding projects is also important, especially, if the designer and vessel owner have already collaborated in previous projects. This will facilitate a better and more effective communication and understanding between the parties, thus, creating lower uncertainty and contributing to a more effective concept design process.

In the following chapter, I explore these five factors (*context*, *agent*, *input*, *model* and *process*) more in detail. Five real ship design user-cases are presented to enhance the understanding of these factors. In each of the five user-cases presented in the next chapter, I explore the use of one uncertainty handling strategy as a means to control, protect or reduce uncertainty in ship design processes.

6. Real ship design user-cases

The following case studies are examples of how ship designers can manage uncertainty in ship design processes by means of utilizing some of the methods, approaches and tools reviewed in the literature review and theorization chapters of this thesis. The objective of this chapter is threefold. Firstly, to relate the independent factors of our research model to practical elements of a ship design process. Secondly, to connect the findings from our analysis of the research model with the literature reviewed in Section 2.3 regarding strategies for handling uncertainty. And third and last, to provide ship design practitioners with user-case material that can be directly related to their ship design projects.

These case studies are based on real projects at Ulstein International AS, where we have made use of the knowledge gained as part of this research work applied on practical user-cases. All the data has been anonymized, where necessary, in order to avoid any identification of the projects, vessels or companies involved.

6.1. Scenario planning as a means to *control input* uncertainties

The design of a new vessel requires the definition of two critical elements: capacity and capability. When launching a new concept design, ship design firms have to balance the capacity and capabilities of the new vessel concept with the needs and demands of the market. In this case study, the ship design company had to identify the cargo carrying capacity and lifting capacity for a new wind farm installation vessel. To do so, three conceptual design alternatives were benchmarked with existing vessels in the market in terms of their contribution to the overall Levelized Cost of Energy (LCOE). Two scenarios, a short-term and a medium-term perspective were included in the study in order to evaluate the market potential of the different alternatives.

Taking as bases recent studies on the operation of wind farm installation vessels like Hansen and Siljan (2017) and Lacal-Arantegui *et al.* (2018), we calculated the contribution to the LCOE of the different vessel designs by considering the time required for the installation and the equivalent daily costs of each design alternative. Based on a set of pre-defined assumptions, we could benchmark the four design alternatives in the two scenarios proposed, as presented in Table 6-1. Project yield and annual project yield were calculated assuming a given revenue per installed turbine. For Scenario I, we assumed 450 000 USD/turbine, and 500 000 USD/turbine for Scenario II.

Table 6-1 Benchmarking of alternative wind farm installation vessel designs; scenario I (left) and scenario II (right).

Scenario I	Alternative A	Alternative B	Alternative C	Vessel X	Units
Capacity	6	8	12	6	Turbines
Port time	13	13	13	13	Day
Jacking time	30	30	30	30	Day
Installation time	50	50	50	50	Day
Sailing time	11	8	6	11	Day
WoW	27	21	17	33	Day
Total time	131	123	115	138	Day
CAPEX	56 200	60 800	88 600	67 500	USD/day
OPEX	100 000	100 000	100 000	100 000	USD/day
VOYEX	20 000	20 000	20 000	20 000	USD/day
Total installation cost	23 142 063	22 214 186	24 015 075	25 828 125	USD
Equivalent dayrate	176 200	180 800	208 600	187 500	USD/day
LCOE	1,67	1,61	1,74	1,87	USD/MWh
Days per MW	0,36	0,34	0,32	0,38	Day
Days per turbine	2,19	2,05	1,92	2,30	Day
Turbines per year	150	160	171	143	Turbines
Project yield	3 857 937	4 785 814	2 984 925	1 171 875	USD
Annual project yield	9 649 268	12 795 558	8 517 245	2 794 635	USD

Scenario II	Alternative A	Alternative B	Alternative C	Vessel X	Units
Capacity	3	4	6	3	Turbines
Port time	19	19	18	19	Day
Jacking time	30	30	30	30	Day
Installation time	70	50	50	70	Day
Sailing time	31	23	16	31	Day
WoW	38	21	17	47	Day
Total time	188	144	131	197	Day
CAPEX	56 200	60 800	88 600	67 500	USD/day
OPEX	100 000	100 000	100 000	100 000	USD/day
VOYEX	20 000	20 000	20 000	20 000	USD/day
Total installation cost	33 130 118	25 954 486	27 239 683	36 937 500	USD
Equivalent dayrate	176 200	180 800	208 600	187 500	USD/day
LCOE	1,20	0,94	0,98	1,33	USD/MWh
Days per MW	0,26	0,20	0,18	0,27	Day
Days per turbine	3,13	2,39	2,18	3,28	Day
Turbines per year	105	137	151	100	Turbines
Project yield	-3 130 118	4 045 514	2 760 317	-6 937 500	USD
Annual project yield	-5 468 636	9 257 530	6 943 949	-11 568 369	USD

Scenario I relates to a wind farm with 60 turbines of 8 MW, this was representing a typical situation for the year 2020. In this scenario, the largest unit alternative *C* is penalized due to its higher costs and could not realize any advantage from its larger cargo-carrying capability and lifting capacity. In Scenario II, however, this design alternative was showing a higher performance, while the smallest alternative, alternative A, and the existing vessel design, vessel X, were underperforming. Scenario II represented a typical wind farm in the year 2025, consisting of 60 turbines of 12 MW. Overall, the design alternative with higher performance was alternative B.

Based on the findings from this user-case study, we can conclude that alternative B was the more attractive of the three alternatives studied and was suggested to be further developed. Hence we cannot predict the future, we can only study how different design solutions will perform in alternative future scenarios and take decisions accordingly.

6.2. Multifunctionality as a means to *protect/exploit context* uncertainty

The revenue-making capability of a vessel is strongly dependent on market conditions. In general terms, the revenue of a commercial vessel can be defined by two factors, the utilization rate (a proportion of the number of days per year the vessel is operating on a contract) and the equivalent dayrate (daily charter per day). These factors are mostly driven by external factors (such as supply, demand and general economic development) that, to a large extent, cannot be controlled by the shipowner. However, there is room to influence the revenue-making capability of a vessel by protecting and exploiting *context* uncertainty. In this case study, we show how ship designers can integrate capabilities in a vessel design to prepare it to handle future uncertainty. The design of a factory stern trawler is reflected.

The revenue-making potential of a factory stern trawler is defined by two factors: the fish quota available (equivalent to utilization) and fish prices (equivalent to dayrate). The quota level defines the number of allowable catches the vessel is eligible to catch each year. This value is adjusted annually by the different governments based on studies of available biomass for each fish species in a given region. Similarly, the volatility of fish prices is driven, principally, by supply and demand. Thus, there is little a fishing company can do to reduce the effects of these external factors if the vessel is not designed to handle such uncertainty. Figure 6-1 reflects the potential revenue creation of a Norwegian factory stern trawler as the product of the quota level times the average fish price for a specific year. The graph reflects a revenue variation between 58 and 96 million Norwegian kroner (NOK) per year. While the vessel has experienced a substantial variation of revenue over the years studied, its costs remained considerably stable, resulting in a potential loss on those years with lower revenue.

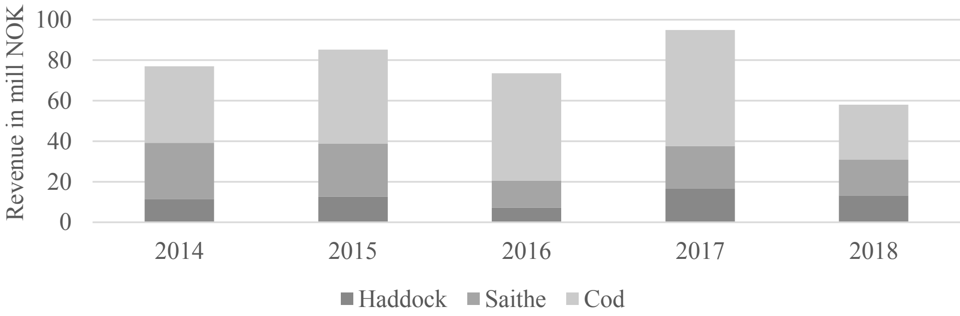


Figure 6-1 Revenue making potential of a Norwegian factory stern trawler (2014-2019).

There is, however, room for designing the fishing vessels with capabilities to handle uncertainty regarding fish prices or quota levels and reduce the negative effects on the overall revenue making capacity of the vessel. Designing a factory stern trawler for a Norwegian fishing company, we explored the role of a shrimp factory onboard the vessels as a capability to increase the flexibility of the vessel design to manage the volatility of fish quota levels and ensure a smoother development of the revenue made by the vessel over its lifecycle. Contrary to white fish, shrimp is not regulated by quota levels. Thus, having a shrimp factory onboard gives the vessel the ability to catch shrimp those years when the quota level of white fish is low. The additional revenue from catching shrimp helps stabilizing the revenue of the vessel and handling uncertainty regarding future quota levels. The cost, space and weight consequences were minimal.

Fish price and quota levels are predominantly outside the control of vessel owners. Yet, these uncertainty factors can be catered for during the ship design process if they are identified in early phases. In this case, the design and the future commercial operation of the vessel are planned to cater for future uncertainty regarding fish prices and quota levels and their effect in the revenue-making capacity of the vessel.

6.3. Performance benchmarking as a means to *reduce process* uncertainty

Vessel performance benchmarking has already been introduced in Section 2.5.1 of this thesis. The purpose of benchmarking a vessel design with peer vessels and designs can be split into two elements: (i) evaluate the performance of a vessel design in comparison to peer, recognisable vessels in the market, and (ii) identify potential room for improvement by comparing the performance of the vessel design with the best vessel performance Pareto front of the market. Furthermore, performance benchmarking can be used as a reference both, the designer and the vessel owner, to decide what is a good enough design, or select areas of improvement. This will reduce the perception of *process* uncertainty since the vessel owner will have control over the design process.

At Ulstein, we have used performance benchmarking for more than four years. Figure 6-2 reflects an application of this methodology in the development of an exploration-cruise vessel. The graph represents the Ulstein general performance index (UGPI) divided by the newbuilding price for a set of vessels distributed along with their capacity in terms of the number of passengers. The triangle from Figure 6-2 represents the concept design under evaluation, while the circles represent peer cruise vessels in the market. The dashed line indicates the best performing vessel Pareto front of the sample, in other words, the vessels with the highest UGPI/price for each passenger capacity level. The concept design under evaluation is in the proximities of the Pareto front, within the 10 percentile which is considered as very favourable. Further optimization during the basic and detail design phase should bring the performance of the vessel design up to the very Pareto front level or beyond it.

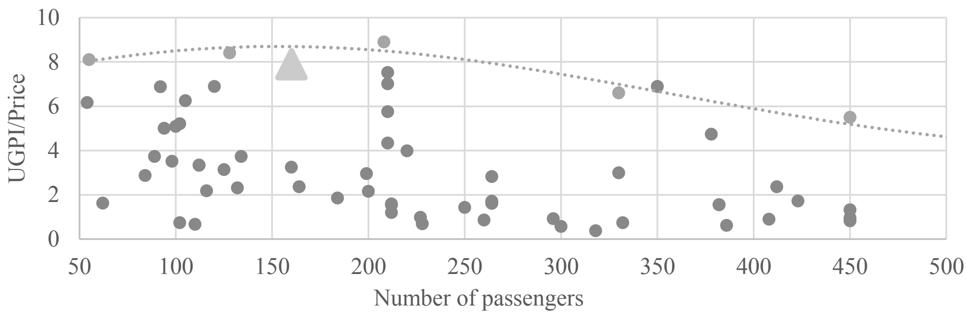


Figure 6-2 Performance benchmarking plot for an exploration-cruise vessel (No. passengers vs UGPI/price).

Vessel performance benchmarking provides a reference to ship designers and ship owners with regards to the maturity of the project and the vessel design. It gives a measurement of certainty regarding how good a design is with respect to existing vessels in the fleet. Thus, vessel owners can be comfortable when ordering a new vessel, since they can benchmark it with well-known existing vessels.

6.4. Fast-track design as a means to *control model* uncertainty

At Ulstein, we have developed a fast-track vessel concept design analysis (FTCDA) tool, a unified design platform containing a set of interconnected statistically-based analysis modules associated to the different aspect of ship design: Newbuilding cost estimation, steel weight calculation, stability evaluation, power estimates, onboard space allocation, etc (Ebrahimi, Brett and Garcia, 2018). The tools are used to developed balanced concept designs. Relying on a holistic ship design perspective, the fast-track design tool gives the designer control of the design process. Relying on a simplification of calculations (ranging from 90 to 98% accuracy), the designer gets, instantaneously, feedback on the consequences of his other decisions and, therefore, can make informed decisions without extending unnecessarily the design process.

Understanding the consequences of each design decisions enables a lower perception of *model* uncertainty. The design process is no longer a black-box where ship owners are not sufficiently informed about the consequences of the design decision to the performance of the final vessel design.

6.5. Market research as a means to *reduce agent* uncertainty

When developing a new vessel design, whether it is an internal development or a vessel for a specific client, the ship designer needs to identify a set of relevant stakeholders to involve in the project. Classification society, interior designer, suppliers, etc; the role of those stakeholders is to support the ship designer along with the project of the vessel. The experience of these stakeholders (*agent*) was identified, in our study, as an important factor contributing to the perception of uncertainty. It is, therefore, important, to select a set of reliable partners for the project to ensure its effectiveness.

At Ulstein, we use fleet data to identify attractive partners for our projects. For each new project, we identify relevant stakeholders with experience in the market. Shipyards, suppliers of main equipment such as engines or topside equipment, and brokers or vessel investors that can increase the informative strength of the business case. An example is presented in Figure 3-1. In this example, we explore attractive engine brands to be involved in a project relating to a factory stern trawler. Figure 3-1 represents the number of stern trawlers contracted after 01.01.2010 distributed by engine brand. The data includes a total of nine engine brands (company A to I), ranging from one vessel and up to twenty vessels. The large deviations among companies suggest that selecting company A, B, C or D will have a positive effect on the perception of uncertainty and consequently, the effectiveness of the design process.

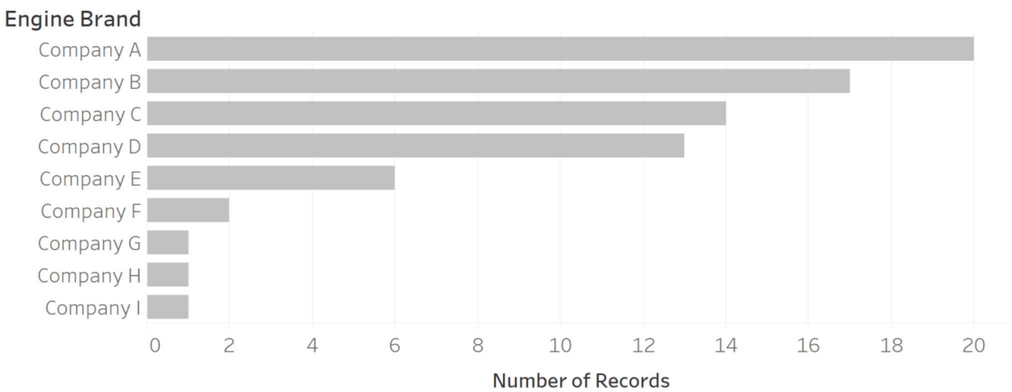


Figure 6-3 Overview of engine brands within the factory stern trawler segment.

7. Discussion

This chapter summarizes my research work, the process, its findings and limitations. The first section summarizes the research process and explains how different activities have interconnections with each other. The second section addresses the research papers produced by this research and how they relate to the six research activities constituting my research work. The third and last section elaborates on the limitations of this research.

7.1. PhD research process

This research work has been carried as part on an industrial PhD program supported by the Norwegian Research Council and Ulstein International AS. The research work lasted for 46 months (3 ¾ years), starting in January 2016 and finalizing with the delivery of the thesis in October 2019. This represents 8 additional months as compared to the original plan. The main reason behind this delay or project extension was an accident that has temporarily limited my capacity to carry out PhD work in the middle of the PhD process, Q4 2017 and Q3 2018. An overview of the activities carried out over the 46-months period is included in Table 7-1.

As part of my industrial PhD scheme requirements, I spent two and a half years (2016, 2018 and part of 2019) at the facilities of the industrial partner (Ulstein International AS) and one year (2017) at the research institution (Norwegian University of Science and Technology). Additionally, and during the first and second year, the PhD candidate also participated in a series of workshops in Boston at the Massachusetts Institute of Technology (MIT) from which my main article 1 was developed.

Considering the agreed-upon plan, the research work was organized as follows: (i) the first year was focused on exploring the research problem, including literature review, some course work and participation in conferences to further discuss the topic with other researchers. (ii) The main focus of the second year was to complete the course work, at the same time that the candidate explored and summarized most of the literature review work and defined the investigative model. (iii) The third and last year was left to collect and analyse data and finalize the publication-work already initiated in the second year.

Most of the supporting articles (SA) were written during the initial phase of the research work. There were three main intentions behind doing so: (a) initiate literature review work that required contemplation and reasoning. (b) Write ideas and receive feedback when presenting it at international conferences, and (c) improve scientific writing skills towards future journal articles and thesis work. During this period, I wrote three articles that were presented for both, a ship-related audience such as those attending *Design for Safety Conference* - supporting article II (Garcia, Brandt and Brett, 2016a) , and *International Conference on Ships and Offshore Structures* – supporting article III (Garcia, Brandt and Brett, 2016b), and for more generic audience like the *Systems of Systems Engineering Conference* – supporting article I (Garcia *et al.*, 2016). The fourth and last conference article was written at a more mature phase of my research and presented at the *International Marine Design Conference* in the Summer

2018 – supporting article IV (Garcia *et al.*, 2018). This last article already discussed and exemplified some of the findings from my research, including a simulation model to quantify the consequences of uncertainty in ship design.

Contrary to conference articles, the journal publications and main articles of my research work were written at a later stage of my research period. The first main article was written in conjunction with two other PhD candidates with complementary research questions. This article was written during the second year and was published in a practical ship design publication, *Journal of Ship Production and Design* – main article 1 (Pettersen *et al.*, 2018). As a follow up of this article and building on the same case material, I wrote a second article for a broader audience and finally published it at *Research in Engineering Design* – main article 2 (Garcia *et al.*, 2019). The third and fourth journal articles, corresponding with main article 3 and main article 4 were written in the latter stages of my research and reflecting the main findings of my overall research work. Main article 3, submitted to *Ship Technology Research* explores the role of information in the design, a recurring topic in this journal. Finally, main article 4 summarizes the development of my research model, data gathering, processing and interpretation of results. This last article has been submitted to *International Shipbuilding Progress*. Thus, the publication of the four main articles have been distributed among ship-related publications and generating design and more generic engineering design journals. As a consequence of writing the last two main articles at the latter stages of the PhD work, they remain under review and have not been accepted for publication yet.

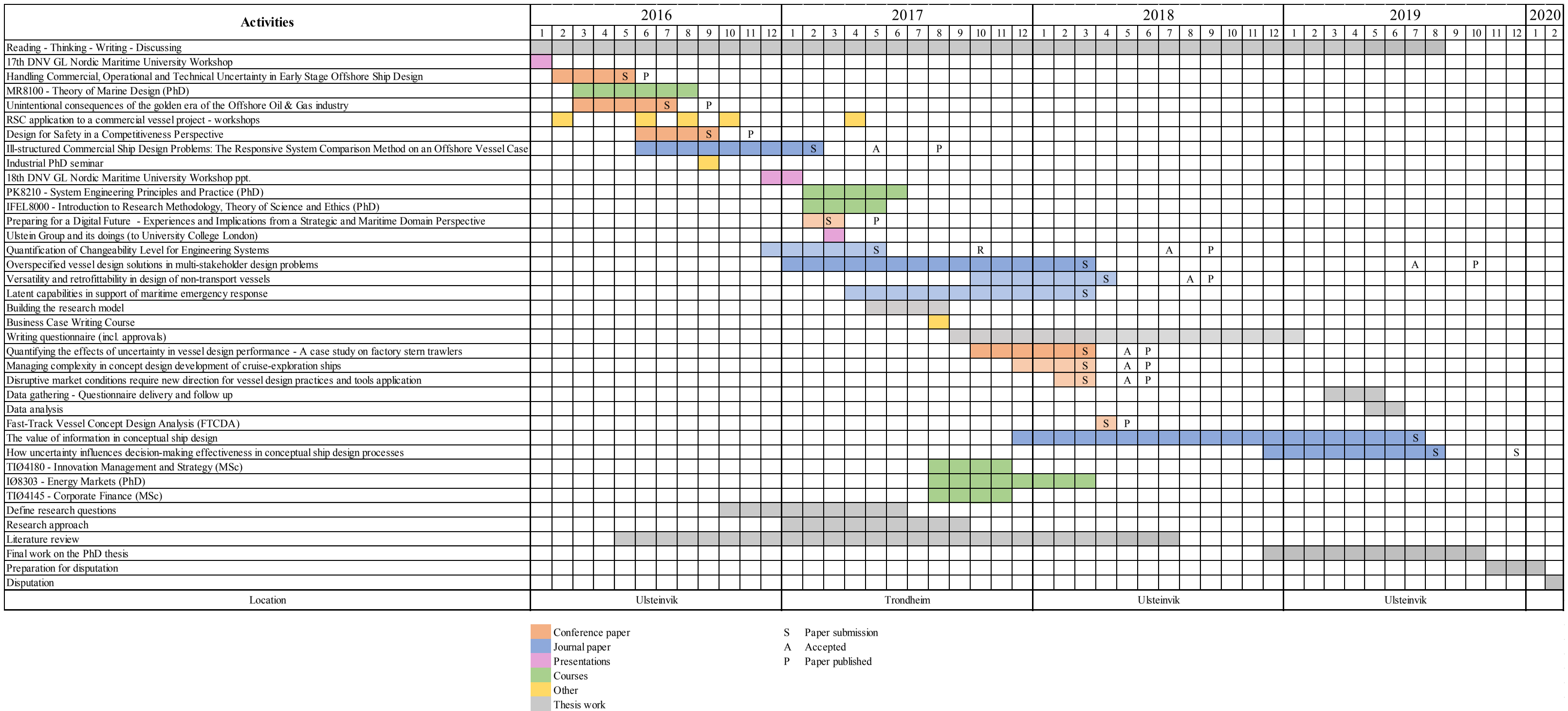
This research work has further included participation in six educational training courses. As already mentioned, most of this activity took place during the second year, with exception of one course that was taken at the beginning of the PhD program to support the structuring of my literature review and problem focus. One of the courses, IFEL8000 - *Introduction to Research Methodology, Theory of Science and Ethics*, elaborates on the principles of research and was used as a foundation to undertake this research work. Further, the course MR8100 - *Theory of Marine Design*, elaborates on the principles of ship design, the design process, and the role that decision-making has in it. As an expansion of this course, the PK8210 - *System Engineering Principles and Practice*, served to put the design process into a holistic perspective, for me raising the importance of contextual and behavioural factors. These courses were used as bases for identifying and understanding the problem at hand, and, therefore, were part of the early stages of my research work. Later in the process, three additional courses provided foundations to study uncertainty, and methodology to handle it. Three alternative perspectives were applied to explore these issues. Firstly, TIØ4180 - *Innovation Management and Strategy*, gave a vision of uncertainty from a new product development perspective, including studies on probe and learn and decision gate methodology. Further, IØ8303 - *Energy Markets*, elaborates on market volatility and real options theory as bases to cope with such irreducible uncertainty. The extracurricular course TIØ4145 – *Corporate Finance*, elaborates on managerial techniques such as portfolio theory, to compensate for potential negative consequences of uncertainty.

Further, and as a premise to test my investigative model with multivariate regression analysis, an online survey was carried out to collect data. The questionnaire used in the survey was developed with the support of literature and grounded methodology, during the third year. This process included a pilot test and a pre-test to calibrate the validity of the instrument. The online survey took place during the Spring of 2019. Data analysis, conclusions and discussions followed during the late Spring and early Summer of 2019.

The structure of my research work overtime is presented in Table 7-1. The writing of this thesis was developed over the 46-months period and following the recommendation of my supervisors for “read – read – read, think – think – think, write – write – write”, to which I add “discuss – discuss – discuss”.

In addition to the activities directly related and reflected in this thesis, I have been involved in commercial vessel design projects where I have operationalized the findings from his research work. Some of those applications are reflected in this thesis. Further, I have contributed as a reviewer at international conferences and journals, including the *Systems of Systems Engineering Conference* and *Research in Engineering Design* journal. This has been very useful to identify literature review material and current state-of-the-art discussions on topics related to my research work. Supervision of master theses was also part of the research period. I was also co-supervisor of two master thesis at the Department of Marine Technology at NTNU and one at Delft University, and supported six others, at different universities including NTNU and University of South-Eastern Norway.

Table 7-1. Research work timeline.



7.2. Research work plan

The research problem identified and analysed in this research work has been operationalized through one research question (RQ):

What are the important uncertainties in conceptual ship design, and how do they influence effective decision-making?

To answer this RQ, the research work has been structured in six research activities (RAs). These activities are linked to the steps associated with the exploratory design research used as a central method for this thesis. The structure of the research work and the relationships among the research questions, research activities and publications are represented in Figure 7-1. The main findings are included in the four main articles (MA) and summarized in this thesis. Further, relevant supporting material and a literature review are also part of the literature review chapter of the thesis and the five supporting articles (SA). A list of main articles and supporting articles is included in Appendix F and Appendix G respectively.

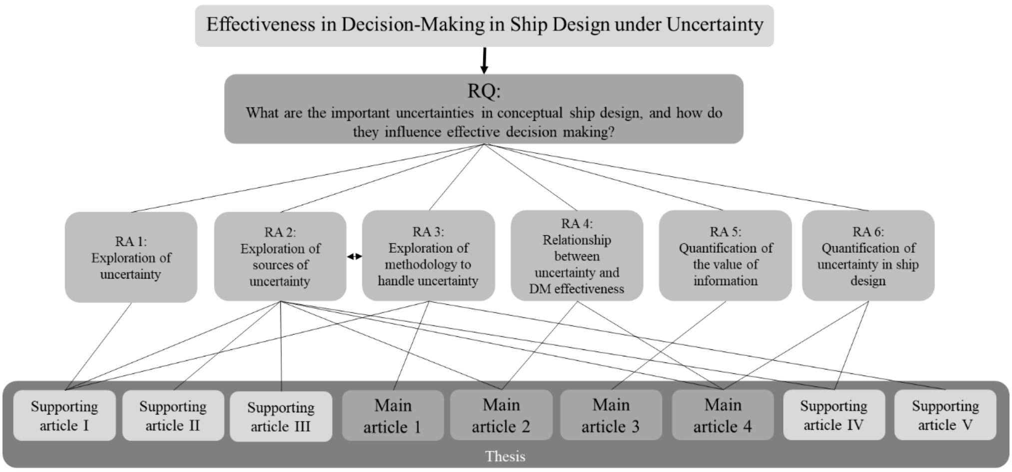


Figure 7-1. Overview of research work plan.

The six research activities were initially thought of as a progressive and linear development of the research work. My first objective of this research was to increase my understanding of uncertainty; more specifically the role of uncertainty in conceptual ship design processes. This activity guided towards the second research activity. Where is uncertainty coming from? What is creating it? These two activities are central in the development of the literature review work covered in this thesis, and created the bases for the supporting articles 1, 2 and 3, as reflected in Figure 7-1. Main article 2 was also a result of the work carried out as research activity 2, and the role of multiple stakeholders in the generation of uncertainty in conceptual ship design processes.

With a better understanding of uncertainty and its sources, a logical next step was to explore the available methodology to handle this uncertainty in decision-making processes. Different methodologies for handling uncertainty are summarized in the literature review chapter of this thesis, and a brief is included in supporting article I. Main article 1 and supporting article V include a study of two specific methodologies; the Response Systems Comparison method in the first case, and versatility and retrofitability in the second.

From this point on, the research work was carried out in parallel among research activities 4, 5 and 6, as opposed to the linear progression on research activities 1, 2 and 3. Research activity 5 and research activity 6 are a consequence of research activity 3. Uncertainty handling requires understanding the value of new information and the effect uncertainty can have in decisions. These two research activities focus on the quantification of these two aspects of uncertainty handling. The value of information is discussed and explored with a practical application in main article 3. Similarly, supporting article IV includes the quantification of the effects of uncertainty in the performance of a factory stern trawler. Research activity 4 explores the relationship between uncertainty and decision-making effectiveness. This activity builds on the findings from the literature review study of research activities 1 and 2. The different sources of uncertainty identified in research activity 2 were modelled as items of an investigative model to explore the relationship between uncertainty and decision-making effectiveness through multi-variate regression analysis. The work carried out in this research activity 4 includes the distribution of a questionnaire through an electronic survey. The findings from the survey and the regression analysis are included in this thesis and summarized in Main article 4.

Furthermore, the research work has been complemented with some practical applications that are included in Chapter 6 of this thesis. The objective of these practical cases is to demonstrate that some of the uncertainty handling strategies reviewed in the literature review work can be readily applied to the daily activities of ship designers to support their decision-making processes. Each of the five case studies included in Chapter 6 relates to one of the five independent uncertainty factors of our research model. In the first case study, I implemented scenario planning theory to support the selection of the size and capabilities (*input* uncertainty) of an installation vessel for the offshore wind energy generation market. The second case study explores a passive value robust strategy, where a factory stern trawler is equipped with a shrimp factory to reduce the negative effects of changes in quota levels or fish prices (*context* uncertainty). *Process* uncertainty is explored in the third case study, where we propose performance benchmarking as a means to reduce uncertainty regarding what is a better vessel. The fourth case study exemplifies the use of fast-track design tools as a means to reduce *model* uncertainty by providing immediate feedback on the causes and consequences of decisions during the conceptual design phase. The fifth and final case study studies market research as a means to reduce *agent* uncertainty by exploring the historical behaviour of the stakeholders involved in the ship design process.

7.3. Limitations

This research studies uncertainty in conceptual ship design, and its effect on the effectiveness of the decision-making process. The research work is framed by the four perspectives or paradigms selected to explore the research question initially identified. The selection of the research perspective is based on the proximity and relation of the topics with the research perspectives, but also on the background and interest of the PhD candidate. It is recognized that the selection of alternative perspectives could have led to alternative or complementary interpretation of the research findings, as suggested by a few authors in the literature (Pennings and Smidts, 2000; Weber, Blais and Betz, 2002; Wang, Feng and Keller, 2013; Schoemaker, 2019).

As a consequence of the selection of the research perspective, this research has focused on a holistic exploration of uncertainty in conceptual design processes. The objective of this thesis was to explore the *wicked* problem characterizing conceptual ship design from a broader and more holistic perspective. Hence, the level of detail to which each uncertainty item has been explored is limited. Downstream activities taking place in the ship design process are related to as part of the research but are not the central topic of the thesis. As an example, the use of design margins in the basic and detailed design phases is, by itself, a separate and complementary research area but is not elaborated upon in this research work. Thus, this study and its findings provide an umbrella to integrate complementary research on the deeper study of the uncertainty factors here predicted.

Another aspect of limitation to this research is the fact that the analysis of perceptual uncertainty is limited to one of the multiple stakeholders involved in a conceptual ship design process. The quantitative part of this research is limited to a targeted audience including ship owners, ship operators and ship managers. The purpose of targeting only this audience was to explore the perception of uncertainty from a customer point of view. Future research may expand this analysis to ship designers, shipyards and suppliers, among others. The findings and research model of this thesis need to be validated, to ensure the generalizability of the results and the appropriateness of the model to the general population.

The response rate achieved from the survey is slightly below the minimum level recommended of 5:1 with respect to the number of independent and dependent variables (Hair *et al.*, 2010). Thus, such a response rate limits the generalization of results and suggest that the findings from this study should be interpreted accordingly.

It is also a limitation to this research that exploratory factor analysis could not be performed. Thus, the analysis was limited to the research model initially proposed. The reason for this impediment was the lack of sufficient respondents to the survey. However, with the revised and scaled-down survey questionnaire based on the findings of this study and an improved sample size such an analysis could most likely be performed and more significant results be derived. However, there are reasons to believe that the results of such exploratory factor analysis would not deviate to a large degree from the proposed model in this research. This belief relies on the fact that my research model was grounded in relevant literature on ship design and decision-making under uncertainty.

Another dilemma in selecting the final research method was whether to use objective or subjective measures of uncertainty. As discussed in Section 2.3.5 of this thesis, there is no agreement in the literature regarding, which of these two representations of uncertainty has more validity or is preferable. For this specific research question and considering that this research work explores uncertainty in conceptual ship design from a holistic perspective, a subjective measurement of uncertainty was considered to be the more appropriated. This choice was based on two considerations. Firstly, most of the management and decision-making literature studying uncertainty from a holistic perspective have chosen this path, contrary to those studying single factors of uncertainty that rely on objective evaluations extracted from risk management literature. And secondly, due to the lack of objective data availability for all the potential factors affecting uncertainty in conceptual ship design.

8. Conclusions

This chapter summarizes the contributions of this PhD research work and reviews the implications to ship design practitioners and academia, including suggestions for future research efforts. The first section summarizes the findings from the literature review and relates them to the results from the multivariate regression analysis presented in Chapter 5 of this thesis. Then, in the second section, I highlight the contributions of this research work. Following, there are two sections reviewing the implications to ship design practitioners and academia. Building on the limitations of this research work, we propose avenues for further work in Section 8.5. Complementary research and alternative avenues to expand knowledge on how uncertainty affects the effectiveness of conceptual design processes are being addressed. The final section contains personal remarks on the experience of performing this research work and my learning from it.

8.1. Concluding remarks

Uncertainty is inevitable in almost everything we do. In ship design, uncertainty is quite prominent and frequently appearing, and its effects can be profound to the effectiveness of the design process. However, ship designers can manage this uncertainty in their decision-making processes via multiple strategies. They can (a) ignore that the uncertainties and all the information necessary is available and no changes will occur, (b) delay it, delay their decisions and await for more information – for example, a change in the market, (c) actively reduce this uncertainty before making a decision, or finally, (d) accept it and be prepared for its consequences.

In this thesis, I have explored some of the most commonly used and researched strategies to handle uncertainty in decision-making situations, with emphasis on its appearance in ship design processes. In general, literature and practice suggest that ignoring uncertainty through deterministic optimization is a popular practice in the ship design industry. Yet, it represents a weak strategy to make decisions affecting systems operating in dynamic environments, with long lifecycles and involving colossal values. Most of the ship design projects ignore the uncertainty around the so-called customer requirements and optimize a vessel design without having a clear idea of the context for such requirements. One reason for this behaviour is the complexity induced by incorporating uncertainty in the decision-making process. This additional complexity leads to the situation that many decision-makers, consciously or unconsciously, omit uncertainties in their daily operations.

Ship design theorists have put special effort into handling uncertainty in the earlier phases of the conceptual design process. Decisions at this stage are critical for the effectiveness of the design process and its outcome and output. Thus, the value of information at this early stage is substantially higher than at later stages of the ship design process. For this reason, design theories such as concurrent engineering and set-based design advocate for delaying decisions awaiting more information to become available. Both, concurrent engineering and set-based design practices have been applied to ship design processes. Yet, they only cover one of at least five critically important and influential factors of uncertainty predicted in this thesis, *model*. Hence, although they can be a good approach to improve the efficiency of the design process, they should be complemented by other techniques to ensure a more effective overall ship design process. However, most of the ship design practice still relies on "probe and learn" techniques, which although very popular in innovation projects in other industries, do not seem to be as effective in ship design projects. Not at all, when the initial expectations of relevant stakeholders are ill-structured.

Strategies for the reduction and the control of uncertainty are not extensively used in the ship design industry. Although literature provides multiple techniques to reduce uncertainty in projects, the way ship design projects are run today doesn't facilitate its implementation. Section 2.4.2 suggests that most of the ship design projects where design firms are involved are based on open tender processes. These processes involve multiple design firms working on the bases of a set of customer requirements given in the tender. This arrangement limits the exploration of the problem at hand or the context, and the designer is confined to a very narrow set of design alternatives. Communication is typically and normally limited to phone and email conversation, in many cases via an intermediary or broker. Time is also an important restriction since ship designers have to balance the time they spend reducing uncertainty with the time for designing the ship. Alternative ship design approaches such as Ulstein's accelerated business development (ABD) propose an alternative holistic avenue to the ship design problem. Here, the initial focus is taken away from the vessel design itself and putting more focus on building up the business case in question and communicating it to the stakeholders involved in the design project. The objective is here to reduce *context*, *agent* and *process* uncertainty factors.

As alternative to the ignorance or reduction of uncertainty, or to delaying decisions, ship designers can accept a certain level of uncertainty. As long as the uncertainties relating to a project are recognized, the decision-maker can accept them. This strategy has been the focus of most of the ship design literature over the past decade, as it is reflected in the literature review and theorization chapters of this thesis. Relying on the fact that it is almost impossible to predict the future and considering that ships are built to operate over a relatively long life, academia and industry have accepted to cope with such uncertainty during the operational life of the vessel. Thus, vessels are designed to adapt to the unforeseen by adapting to new conditions. This adaptation can be passive, thus the vessel design is developed and built with extra functions and capacities. Or active, where the vessel is *prepared for* being upgraded during its future operation. There are multiple examples of both strategies in the literature, and a few of them have already been commented upon in earlier chapters of this thesis. Margin is one of the passive methodologies that have been extensively adopted among ship designers. Margins are used to cater for both, uncertainties relating to stakeholder expectations, changes in contextual factors and errors and tolerances in design calculations. As part of this research, we have demonstrated, however, that uncontrolled used of margins can have detrimental effects on the performance of the final vessel design. Design *ilities* such as reliability, multifunctionality, changeability and agility have become more popular in the industry in the latter years. However, they typically drive complexity and costs.

From the findings of my survey, and after having explored the alternative strategies to handle different types and factors of uncertainty, it becomes clear that ship designers have to integrate multiple uncertainty handling strategies in their daily activities. Table 8-1 represents an overview of uncertainty handling strategies and its relation to uncertainty items in conceptual ship design. There is no single strategy that covers all the items identified in conceptual ship design, as reflected in Table 8-1. Delay strategies focus a lot on *model* and *process* uncertainty, while strategies to reduce uncertainty should be oriented towards *context* and *agent* uncertainty. Finally, strategies to protect against the negative effects of uncertainty or exploit positive effects are primarily oriented towards items of *context* uncertainty.

Ship design theories relying on concurrent engineering (Mistree *et al.*, 1990) and set-based design principles (Singer, Doerry and Buckley, 2009) propose a major shift from the traditional ship design spiral (Evans, 1959). These approaches focus on *model* and *process* uncertainty factors only, by elaborating on the interconnections and causal relationships among the different calculations of the ship design process. The objective of approaching the problem as concurrent, in contrast to iterative, is the reduction of the development time by avoiding re-work resulting from decisions taken under uncertainty. Yet, they are limited to technical aspects of the ship design task, thus, not elaborating on the *agent*, *context* and *input* uncertainty factors.

Strategies to reduce and control uncertainty do, however, focus on uncertainty relating to items from these other factors. Techniques from management literature, in many cases borrowed from social science, are particularly directed towards the uncertainty factor *agent*. Understanding and managing stakeholders and their expectations is an important role of the ship designer. He or she is responsible for bringing together the different stakeholders and making them agree on what is a better vessel design for a specific business case. He brings the expectations from the commercial perspective of the owner into the technical domain and provides the shipowner with relevant feedback on what vessel to go for. In this process, he or she involves among other people from his organization, hydrodynamicists, structural engineers, marine engineers, electrical engineers and shipbuilders. The ideas, information and calculations from all these sources have to be collated and communicated to the customer, so his or her decisions are taken under a relevant and appropriate level and scope of information. In the third article of this research work (main article 3) I elaborate on this aspect, and how to balance the amount of information in the ship design process. Computerized tools to manage information, such as PLM and PDM are also important tools to keep all the stakeholders updated about the progression of work. Scenario planning techniques and prognosis exercises are useful tools to include in the business case development and strategize the ship design development in relation to contextual and environmental factors.

Table 8-1. Overview of uncertainty handling strategies and its relation to uncertainty items in conceptual ship design.

Factors	Items	Ignore	Delay			Reduce/Control					Accept /Protect /Exploit								
		Deterministic optimization	Concurrent engineering	Set-based design	Probe and learn	Research	Management & organizational tools	Scenario planning	Communication	Simulation	Digital twin	Margins	Redundancy	Reliability	Multi-functionality	Versatility	Changeability	Flexibility	Agility
Context	Regulations					■	■	■				■							
	Vessel dayrates					■		■											
	Market dynamism					■		■							■	■	■	■	■
	Vessel costs (excl. fuel)					■		■											
	Fuel prices					■		■											
	Future vessel requirements						■	■				■	■		■	■	■	■	■
	Financial factors					■	■												
	Institutions (flag state, eg.)					■	■					■							
	Political constrains					■	■												
	Market conditions					■	■	■							■	■	■	■	■
	Tax policies					■	■												
	Vessel demand							■							■	■	■	■	■
	Vessel supply							■							■	■	■	■	■
	Disasters (wars, terrorism, epidemics)							■				■							
	Changes in vessel's performance							■		■	■	■	■						
	Sea state (waves, wind, current)							■		■		■							
Agent	Communication (with other stakeholders)						■		■										
	Experience					■	■												
	Presence of multiple stakeholders						■		■										
	Relationship between the stakeholders						■		■										
	Skills of the different stakeholders						■												
	Tolerance to ambiguity (your own tolerance)						■		■										
Input	Clarity of project scope						■												
	Lack of information (regarding the needs of the project)					■	■												
	Reliability of information					■				■									
	Operational region (where the vessel will operate)							■				■	■		■	■	■	■	■
Model	Calculation of vessel capacities and capabilities		■	■	■														
	Tolerances		■	■	■							■							
	Estimates		■	■	■					■		■							
	Economic performance					■				■									
	Lack of understanding of the vessel design solution		■	■	■		■			■	■								
	Operational performance (reliability)									■	■	■	■	■					
Process	Technological innovation					■	■			■									
	Failure (errors)										■	■	■	■					
	Goodness of fit				■		■			■		■							
	Lack of knowledge of the process				■	■	■												
	Lack of knowledge on causal relationships		■	■	■	■				■	■								
	Vessel design changes (after newbuilding contract)							■		■	■	■	■		■	■	■	■	■

The third and last group of strategies relies on accepting the uncertainty in the ship design process and preparing the vessel design to protect against or exploit the benefits of it, when and if uncertainty arises. The characteristics of how the vessel design is prepared to handle future uncertainty are commonly used and recognised as ilities. These ilities are abstract qualities of a design. Versatility, reliability, multi-functionality, flexibility, agility and changeability are some examples. These strategies are organized into two groups. One group of ilities protects against the effects of uncertainty passively. In other words, the vessel design is prepared to handle future uncertainties from its delivery from the yard “as-built”. Multi-functionality, for example, represents the ability of a vessel to perform more than one function or activity. Thus, if the demand for an activity decreases or if one of its functions underperform, the vessel can be used to perform another activity or relocated in another market. Contrary, the second group of strategies rely on active protection. Changeability, for example, relies on preparing the vessel design to be adapted after an uncertainty has arisen.

Margins are another example of passive protection against uncertainty. Margins can either be placed to mitigate uncertainty in the design process, such as margins over the speed of the vessel, or included in the design to handle changes in the future operating context. The former is known as safety margins, while the latter is referred to as design margins. In spite of being one of the most common strategies to handle uncertainty in ship design, margins can result in overspecified designs with negative consequences for the performance of the vessel over its operational life (Garcia, Brandt and Brett, 2016a). One example of design margins is the inclusion of ice-class strengthening on vessels that will initially operate in warmer waters. It is common that some ship owners request to include ice strengthening in their vessels. In some cases, low strengthening such as C and 1C, but in other cases, strong ice strengthening such as 1B or 1A, that is only required in areas with a substantial presence of ice such as in the Baltic Sea. It is not uncommon to see Ropax vessels being built for operation in Mediterranean waters with ice strengthening 1A. Such operational arrangements are examples of a lack of understanding of the consequences and implications of overspecifying the vessel eventually with detrimental vessel performance effects. The argument behind such a decision is a potential future sale of the vessel to operators in the Baltic Sea. Yet, companies operating vessels for ice-infested waters have never purchased second-hand tonnage from operators in benign and tempered waters. Fishing companies are also known for using ice strengthening as a margin in their vessels. In this case, ice strengthening is seen as a life prolongation for the vessel and a likely reduction of maintenance work. Ice strengthening has, however, negative consequences for the performance of the vessel when this is operating outside ice-infested waters. A heavier vessel as a consequence of the additional steel will cost more to build and will have higher resistance, resulting in higher fuel consumption. Further, a propulsion system designed to operate in ice-infested waters will have poorer efficiency than conventional propulsion systems, therefore having higher energy and fuel consumption.

8.2. Evaluation of contributions

The importance of understanding the effect that uncertainty can have on the effectiveness of the design process and the performance of the vessel design over its lifecycle is reflected by the growing interest shown for this research topic in academia. This research provides new insights into the relationship between uncertainty and the effectiveness of the conceptual ship design process from the perspective of the ship owner. This research work has also expanded theoretically the understanding of what factors generate uncertainty in ship design, and what strategies are available to the ship designers to mitigate them during the design phase. Overall, this research work can be summarized in eight contributions to research on uncertainty in ship design processes:

Contribution 1: this research work proposes a summary model of different uncertainty handling strategies categorized by their type of action, see Section 2.3. The model is used further in the concluding chapter of this thesis to relate the different strategies to items of uncertainty. This model and the resulting Table 8.1 can be used as a reference guide for ship design practitioners and researchers to select an adequate strategy to handle uncertainty in their daily tasks. Each of the different uncertainty handling strategies included in the summary model is described in the literature chapter of this thesis. The description of the strategies is complemented with anecdotic case studies to explore the practicality of results found in this research work.

Contribution 2: this research work proposes and validates an investigative model to measure perceptual uncertainty and decision-making effectiveness in ship design processes. This investigative model has been operationalized through a questionnaire distributed as an online survey. It is an instrument developed to measure perceptual uncertainty in ship design processes. The unit of analysis is the shipowner as one of the most important stakeholders in the development of the ship design solution. To the knowledge of the author of this thesis, it is one of few measurement instruments now available to study uncertainty in ship design processes.

Contribution 3: this research work identifies and quantifies the perception of uncertainty by shipping companies in the conceptual design phase of new vessel designs. Their individual factors, importance and influence are explored and concluded upon.

Contribution 4: this research work points to areas for improvement for ship design practitioners to reduce the perception of uncertainty in ship design companies and increase the effectiveness of the conceptual design processes.

Contribution 5: this research work has tested the implementation of two frameworks for system design under uncertainty, namely: Accelerated Business Development approach (ABD) and Responsive Systems Comparison method (RSC). The first framework, ABD, is used, to a large extent, by the Ulstein Group in most of our new conceptual vessel design work. The application of the RSC framework is included in the main article 1 of this thesis. The application also reflects a real vessel design case. In the second application, an offshore construction vessel was used as a case study. In both cases, it was found that to become applicable to real design projects, these frameworks and other methods identified in this thesis have to be flexible and adaptable to the resources and needs of each specific case at hand. These frameworks represent means for advancing existing conceptual ship design processes.

Contribution 6: this research work has explored quantitatively the effects of uncertainty in the performance of new vessel design. In supporting article 4 of this research work, the authors quantify the potential effects that uncertainty could have in the performance of a factory stern trawler. This information is used as a reference to prepare the vessel design to future uncertain events and limit the negative effect such uncertainty could have in the economic performance of the vessel over its lifetime.

Contribution 7: this research work has demonstrated the value that additional information can have in the conceptual design phase of a new vessel. In main article 3, the authors propose the use of the concept value of information to support the design of the ship design process; the distribution of resources between exploration and exploitation activities, and what analyses and tools should be used and when.

Contribution 8: this research work has proposed and tested a set of metrics to measure the level of misalignment among stakeholders' expectations and support more effective communication among them.

8.3. Practical implication to ship design practitioners

The findings of this research work suggest that ship designers have to approach the conceptual ship design process with a holistic perspective; identifying, collect and collate critical information earlier in the process than done before, when they start developing the final vessel design solution. The value of information metric proposed in main article 3 can be used as a reference to select what information shall be prioritized in the earlier phases of the design process.

In the current market environment characterising the shipping industry, regulations are considered as the most critical aspect with regards to the effectiveness of the decision-making process. Regulations play a binary role. A vessel design solution can comply with them (or overfulfill) or not comply. For example, if a stern trawler ends up with a 2 501 GT vessel, rather than 2 499 GT as planned, it will be unusable, since Regulators will not give permission for operating the larger vessel because of quota restrictions. The ongoing implementation of stricter environmental regulations has also induced uncertainty into the shipping industry with regards to what type of fuel to use. For example, shipping companies have to decide how to comply with IMO's 2020 emission limits before the 1st of January 2020. The lack of understanding of the development of fuel prices and fuel availability complicate the decision to shipping companies. These two challenges are reflected in two uncertainty items considered of high importance by the participants in the survey, the economic performance of the vessel design and future vessel requirements. The experience of the people involved in the design process is the next factor in terms of importance.

The communication among stakeholders also plays an important role in the design process. Understanding the expectations of the different stakeholders and communicating them among the different parties involved in the process can be challenging. The ship designer can not rely on a "yes to all" behaviour, as this will very easily lead to an overspecified design as demonstrated in main article 2. It is necessary to communicate to the different stakeholders what is possible within the available budget and what is a better solution for the individual and group interests.

This research work provides a guide for ship designers with respect to what items they should focus their resources on. Items with higher relevance (higher mean value in Table 5-4) should be prioritized to those with lower scores.

8.4. Implications for academia

This research work uses research methodology borrowed from management and decision-making literature to explore a problem that historically has been based primarily on theory and methodology from the engineering discipline. This multi-perspective triangulation approach is in itself a contribution to academia and research on ship design, which also opens the possibility for further interdisciplinary research.

The findings of this research provide suggestions to academia, in relation to which direction ship design theories and methodologies should develop to improve the effectiveness of conceptual ship design processes. Although the findings should be further validated and verified before they can be generalized, it is suggested that current master and bachelor of science programs in naval architecture and marine engineering should be strengthen and pay more attention to the early or upstream work process initiatives of a more novel and future-oriented conceptual ship design process, even at the expense of at de-emphasising of the importance of downstream activities like structural strength, hydrodynamic and stability related analysis. The culture of vessel hull and propulsion system optimization dominating today's ship design studies has to be better grounded into a combined technical, operational and commercial context. Firstly, it is impossible to optimize all the elements of ship design. Ship design relies on the compromise of elements and systems onboard. And secondly, optimize for an ideal operational scenario is partly unrealistic, since the vessel will rarely, or never, operate in such conditions over long time.

8.5. Further work

There are multiple avenues to continue the research work initiated and carried out in this thesis. This thesis has already suggested several avenues for continued and future research in earlier sections. Some of these avenues are further described in this section of the thesis. In many cases, these avenues can represent a validation and/or an expansion of the present findings and arise from the limitations of this research discussed in Section 7.3. An intuitive research direction is to expand the study of the effects of uncertainty to downstream ship design activities including basic design and detail engineering. In these advanced phases of the design process, some of the uncertainties identified in the conceptual phase have dissipated, but others will remain and newer will arise that need consideration. Thus, it would be beneficial to understand the development of the different uncertainties along with the successive phases of the ship design process. This research has settled the foundation and expectantly a guideline for how to identify and quantify uncertainty in the design process.

Similarly, and from the perspective of the quantitative work of this thesis, there are, at least, two main reasons for future research work: (i) to validate the findings and ensure the generalizability of the results, and the appropriateness of the model to the general population. Certainly, a repeat study with more participants would open up interesting possibilities. This would require the distribution of the questionnaire proposed to an alternative population of ship owning companies. (ii) To expand the perception of uncertainty to other stakeholders involved in the conceptual ship design process, including ship designers, shipbuilders, suppliers and vessel charterers. This would require the distribution of the questionnaire proposed to participants in those stakeholder groups. My own raw data collected in this research work is available to other researchers who want to validate the results of this research work with further analysis.

This research decided to quantify uncertainty subjectively, relying on the lack of data availability and supported by literature and existing multi-perspective theory. This subjective identification of uncertainty has allowed the identification and quantification of uncertainty items and factors present in conceptual ship design processes. Further research can pursue a broader objective quantification model of uncertainty. Relying on the model proposed, historical data and a simulation model, future research can pursue the direct quantification of uncertainty.

8.6. What I have learnt

The decision of pursuing a doctoral degree relies on two objectives (Feldt, 2012), “developing you [the researcher] into an independent re-searcher” and “changing something for the better”. Both are born on a desire to expand one’s wisdom on an area of interest, which requires firstly, the ability to systematically extract data, create information and develop knowledge; the ability to do research.

This research work has, certainly, enriched my ability to explore a topic, problem or area of interest and systematically expand the knowledge on it. This ability is composed by three elements, learning to read, developing the facility of structuring what has been read and processing it, think, and finally, being able to describe what has been learnt in words, write. Discussions with other doctoral candidates and co-supervision of MSc students have been essential in the process of learning the ability to do research.

Designing ships is, without doubt, a topic of my interest, more particularly in the conceptual phase, where most of the costs and parameters driving the performance of the vessel are decided. Thus, understanding better what factors influence the effectiveness of the decision-making process was of particular interest to me. This is also paramount for design companies, especially those in cost-intensive countries like Norway, where I work. After two years of work-related to conceptual ship design, I have experienced the challenges of the wicked problem.

Starting the development of the technical design solution (general arrangement, stability calculations, weight estimates, hydrodynamic calculations, etc) before fully understanding the business case has led to multiple and unnecessary iterations and re-work. My personal objective with this research work was to identify what factors were critical for attaining a better understanding of and being able to do something with the effectiveness of the design process; and the information that, if available earlier in the process, could lead to a more effective conceptual design process.

Additionally, and at a personal level, the research process leading to this thesis has represented an internal growth process, giving me the privilege of understanding the value of knowledge and enjoying the process of achieving it.

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Appendix A - The survey instrument

A-1: The survey questionnaire instrument

1 General instructions

Definitions:

This questionnaire asks questions about you, your company and the stakeholders involved in the latest vessel newbuilding project you were involved in or associated with.

Your immediate unit includes you, and all the individuals at your department. For example, the finance department or newbuilding department. Your company is including all the units of your company which have been, directly or indirectly, involved in the newbuilding project.

Stakeholders include all the additional stakeholders which have been involved in the new building project, such as ship designer, shipyard, suppliers, banks, etc.

Product is referring to the final vessel design as included in the newbuilding contract.

The current questionnaire focuses on the conceptual design period, being this the process going from the first thoughts and discussions up to the signing of the newbuilding contract.

Questionnaire trivia:

This questionnaire should take no more than 15 minutes to complete.

Most of the questions can be quickly answered by checking boxes, or by selecting one of several numbers that appear on a scale to the right-hand side of the question.

It is important that you try to answer all questions proposed to your best knowledge and capability.

Your answers are very important for properly coding and analyzing the data that you are willing to share with me.

Your identity will be hidden. Read more about confidentiality and hidden identity here. (Opens in a new window)

2 Uncertainty in ship design

Context - To what extent did the following factors influence your decision of selecting a specific vessel design?

In the following questions, we would like you to describe the process followed in the latest newbuilding project you were involved in or associated with.

Scale: (1=Not at all influential, 2=slightly influential, 3=somewhat influential, 4=very influential, 5=extremely influential)

	1 - not at all influential	2 - slightly influential	3 - somewhat influential	4 - very influential	5 - extremely influential	I don't know
Competitors	O	O	O	O	O	O
Regulations	O	O	O	O	O	O
Vessel dayrates (revenue)	O	O	O	O	O	O
Market dynamism (changes in the market)	O	O	O	O	O	O
Vessel costs (excl. fuel)	O	O	O	O	O	O
Fuel prices	O	O	O	O	O	O
Future vessel requirements	O	O	O	O	O	O
Financial factors	O	O	O	O	O	O
Institutions (flag state, eg.)	O	O	O	O	O	O
Political constraints	O	O	O	O	O	O
Market conditions (at the time of signing the newbuilding contract)	O	O	O	O	O	O
Tax policies	O	O	O	O	O	O
Vessel demand	O	O	O	O	O	O
Vessel supply	O	O	O	O	O	O
Disasters (wars, terrorism, epidemics)	O	O	O	O	O	O
Changes in vessel's performance	O	O	O	O	O	O
Sea state (waves, wind, current)	O	O	O	O	O	O

Agent - To what extent did the following factors influence your decision of selecting a specific vessel design?

In the following questions, we would like you to describe the process followed in the latest newbuilding project you were involved in or associated with.

Scale: (1=Not at all influential, 2=slightly influential, 3=somewhat influential, 4=very influential, 5=extremely influential)

	1 - not at all influential	2 - slightly influential	3 - somewhat influential	4 - very influential	5 - extremely influential	I don't know
Beliefs (your own beliefs)	O	O	O	O	O	O
Communication (with other stakeholders)	O	O	O	O	O	O
Experience (your experience with vessel newbuilding projects)	O	O	O	O	O	O
Presence of multiple stakeholders	O	O	O	O	O	O
Relationship between the stakeholders (is it the first project in common?)	O	O	O	O	O	O
Skills of the different stakeholders involved in the project	O	O	O	O	O	O
Tolerance to ambiguity (your own tolerance)	O	O	O	O	O	O

Input - To what extent did the following factors influence your decision of selecting a specific vessel design?

In the following questions, we would like you to describe the process followed in the latest newbuilding project you were involved in or associated with.

Scale: (1=Not at all influential, 2=slightly influential, 3=somewhat influential, 4=very influential, 5=extremely influential)

	1 - not at all influential	2 - slightly influential	3 - somewhat influential	4 - very influential	5 - extremely influential	I don't know
Clarity of project scope	O	O	O	O	O	O
Lack of information (regarding the needs of the project)	O	O	O	O	O	O
Operating strategy (for that specific vessel)	O	O	O	O	O	O
Reliability of information	O	O	O	O	O	O
Operational region (where the vessel will operate)	O	O	O	O	O	O

Model - To what extent did the following factors influence your decision of selecting a specific vessel design?

In the following questions, we would like you to describe the process followed in the latest newbuilding project you were involved in or associated with.

Scale: (1=Not at all influential, 2=slightly influential, 3=somewhat influential, 4=very influential, 5=extremely influential)

	1 - not at all influential	2 - slightly influential	3 - somewhat influential	4 - very influential	5 - extremely influential	I don't know
Complexity of the vessel design solution	O	O	O	O	O	O
Calculation of vessel capacities and capabilities	O	O	O	O	O	O
Tolerances	O	O	O	O	O	O
Estimates	O	O	O	O	O	O
Economic performance	O	O	O	O	O	O
Lack of understanding of the vessel design solution	O	O	O	O	O	O
Operational performance (reliability)	O	O	O	O	O	O
Technological innovation	O	O	O	O	O	O
Failure (errors)	O	O	O	O	O	O

Process - To what extent did the following factors influence your decision of selecting a specific vessel design?

In the following questions, we would like you to describe the process followed in the latest newbuilding project you were involved in or associated with.

Scale: (1=Not at all influential, 2=slightly influential, 3=somewhat influential, 4=very influential, 5=extremely influential)

	1 - not at all influential	2 - slightly influential	3 - somewhat influential	4 - very influential	5 - extremely influential	I don't know
Goodness of fit (how does the design solution satisfy your expectations)	O	O	O	O	O	O
Lack of knowledge of the process	O	O	O	O	O	O
Lack of knowledge on causal relationships	O	O	O	O	O	O
Vessel design changes (after newbuilding contract)	O	O	O	O	O	O
Shipbuilding time	O	O	O	O	O	O

3 Decision-making effectiveness

In the following questions, we would like to explore your perceptions about the effectiveness of the decision-making process relating to the newbuilding project unit of analysis.

Decision rationality - Please, tell us about your perception by marking one of the alternatives that follow each question.

New scale: (1=Never, 2=Rarely, 3=Occasionally, 4=A moderate amount, 5=A great deal)

	1 - never	2 - rarely	3 - occasionally	4 - a moderate amount	5 - a great deal	I don't know
Have you looked for specific information before making a decision?	O	O	O	O	O	O
Have you analysed specific information before making a decision?	O	O	O	O	O	O
Were quantitative analytics techniques important in making the decision?	O	O	O	O	O	O
Have you focused attention on crucial information ignoring other irrelevant information?	O	O	O	O	O	O
How important are analytics in the decision-making process?	O	O	O	O	O	O

Decentralization - Please, tell us about your perception by marking one of the alternatives that follow each question.

New scale: (1=Never, 2=Rarely, 3=Occasionally, 4=A moderate amount, 5=A great deal)

	1 - never	2 - rarely	3 - occasionally	4 - a moderate amount	5 - a great deal	I don't know
To what extent have you delegated decision-making in this project?	O	O	O	O	O	O
To what extent have you tried to reach consensus between the decision group members?	O	O	O	O	O	O
To what extent could you control the decision-making process?	O	O	O	O	O	O
Is the structure of your company characterised by few hierarchical levels in decision-making?	O	O	O	O	O	O

Experience - Please, tell us about your perception by marking one of the alternatives that follow each question.

New scale: (1=Never, 2=Rarely, 3=Occasionally, 4=A moderate amount, 5=A great deal)

	1 - never	2 - rarely	3 - occasionally	4 - a moderate amount	5 - a great deal	I don't know
To what extent was your company familiarized with the operational region?	O	O	O	O	O	O
To what extent was your company familiarized with the vessel segment?	O	O	O	O	O	O
To what extent had your company collaborations (partnerships) in the region?	O	O	O	O	O	O
To what extent was your company present in the market?	O	O	O	O	O	O
To what extent had your company collaborations (partnerships) in the vessel segment?	O	O	O	O	O	O

Intuition - Please, tell us about your perception by marking one of the alternatives that follow each question.

New scale: (1=Never, 2=Rarely, 3=Occasionally, 4=A moderate amount, 5=A great deal)

	1 - never	2 - rarely	3 - occasionally	4 - a moderate amount	5 - a great deal	I don't know
To what extent did decision-making rely on personal judgment?	O	O	O	O	O	O
How much emphasis was placed on past experience from similar decision when making decisions?	O	O	O	O	O	O
To what extent did decision-makers trust their intuition?	O	O	O	O	O	O
To what extent did decision-making rely on gut feeling?	O	O	O	O	O	O
How much emphasis was placed on intuition as a useful decision-making tool?	O	O	O	O	O	O
To what extent did you trust in your intuition?	O	O	O	O	O	O

4 Demographic information

In the following questions, we would like to capture your demographic information. Please, select whichever alternative applies below.

Working experience

O 5 years or less

O 6 to 10 years

O 11 to 20 years

O More than 20 years

of which working in ship-related industries

- O 5 years or less
- O 6 to 10 years
- O 11 to 20 years
- O More than 20 years

Background: Mark more than one alternative if relevant.

- O Engineering
- O Economy
- O Business
- O Captain or chief engineer
- O Other:______________

Number of newbuilding projects in which you have been involved before this

- O None
- O One or two
- O Three to five
- O Six to ten
- O More than ten

5 Project case study

Vessel type

In the following questions, we would like to capture information regarding the newbuilding vessel project. Please, fill in whichever box applies below the preliminary mode of operation of the vessel used as reference when filling in this questionnaire. For example, platform supply vessel, cruise vessel, container vessel, etc.

- O Offshore vessel
- O Merchant vessel
- O Passenger vessel
- O Fishing vessel
- O Other vessel types
- O Platforms and other floating objects

Newbuilding project model

In the following questions, we would like to capture information regarding the newbuilding project model. Please, fill in whichever box applies below. If you feel that none of the categories here included representing the real process, please write your description in the box marked as "other".

- O The vessel was designed and built together with a customer (end-user) for a specific tender
- O The vessel was designed and built together with a customer (end-user) but without a particular project
- O The vessel was designed and built for a tender but without the involvement of the customer (end-user)
- O The vessel was designed and built together with a customer (end-user) for a specific market segment and region

- O The vessel was designed and built for a specific market segment and region but without involvement of a customer (end-user)
- O The vessel was built in speculation
- O Other: ___________________

Newbuilding project operational strategy

In the following questions, we would like to capture information regarding the operational strategy towards the newbuilding project. Please, fill in whichever box applies below. If you feel that none of the categories here included representing the real process, please write your description in the box marked as "other".

- O The vessel was designed and built to be owned, managed and operated by my company
- O The vessel was designed and built to be owned, managed but not operated by my company (Time charter)
- O The vessel was designed and built to be owned but not managed nor operated by my company (Bareboat)
- O The vessel was designed and built to be managed, operated but not owned by my company
- O The vessel was designed and built to be sold after delivery
- O Other: _________________

Role within the newbuilding project

In the following questions, we would like to capture information regarding your involvement with the newbuilding project. Please, fill in whichever box applies below. If you feel that none of the categories here included representing the real process, please write your description in the box marked as "other".

- O Financial manager
- O Newbuilding manager
- O Technical manager
- O Purchase manager
- O Other: ________________

6 Final comments

Please, write below your further comments if any.

---o0o---

A-2: The initial cover letter to accompany the questionnaire

Dear Sir or Madam

I am a PhD associate at the Norwegian University of Science and Technology (NTNU), Department of Marine Technology (IMT), Norway. My PhD research is part of my duties as a business analyst at Ulstein International AS.

The title of my research is "Effective decision-making in ship design under uncertainty". The purpose is to enhance the knowledge of how uncertainty influences conceptual ship design and its complementary decision-making process and therefore, the performance of the vessel over its lifecycle. I expect to develop a model to test whether the different types of uncertainty are influencing the effectiveness of the decision-making process and eventually the vessel design performance, and what factors could intervene in the relationship between decision-making uncertainty and ship design effectiveness.

Please, spare some time to answer this questionnaire, it should take no more than 15 minutes to complete. The information provided by you will be anonymised, and it will not be related to you or the company you are representing. Should you require any explanation or clarification please do not hesitate to contact me, my contact information is provided below in this email.

Thank you for your kind support and cooperation in this important study.

This study has been notified to the Data Protection Official for Research, NSD – Norwegian Centre for Research Data, project number 298033.

Yours sincerely

Jose Jorge Garcia Agis

PhD student – Norwegian University of Science and Technology, Norway

Business Analyst – Ulstein International AS, Norway

Email: jose.jorge.agis@ulstein.com or jose.agis@ntnu.no

Phone: (+47) 944.31.623

Address: P.O. Box 158, NO-6067 Ulsteinvik, Norway

A-3: Reminder letter to the subjects

Dear Sir or Madam

This is a kind reminder for the "Survey on uncertainty in ship design" for which you received an Email on *month and day*. Please, notice that in some cases the email has been stored at the "Junk" mailbox.

As a PhD associate at the Norwegian University of Science and Technology (NTNU), I would appreciate your time in completing this survey, that should take no more than 10 minutes. The purpose of the Survey is to enhance the knowledge of how uncertainty influences conceptual ship design and its complementary decision-making process and therefore, the performance of the vessel over its lifecycle. I will share a summary of my findings with those participating in the survey.

If you have not been involved in a vessel newbuilding project, I would appreciate I you could share this email with someone in your organization that could answer the survey instead.

The information provided by you will be anonymised, and it will not be related to you or the company you are representing. Should you require any explanation or clarification please do not hesitate to contact me, my contact information is provided below in this email.

Thank you for your kind support and cooperation in this important study.

This study has been approved by the Data Protection Official for Research, NSD – Norwegian Centre for Research Data, project number 298033.

Yours sincerely

Jose Jorge Garcia Agis

PhD student – Norwegian University of Science and Technology, Norway

Email: jose.agis@ntnu.no

Phone: (+47) 944.31.623

Appendix B – Demographics of respondents

Respondent characteristics	Number of respondents (n=23)	Percentage (%)
Working experience		
5 years or less	0	0 %
6 to 10 years	2	9 %
11 to 20 years	4	17 %
More than 20 years	17	74 %
Total	23	100 %
Working experience in ship related industries		
5 years or less	0	0 %
6 to 10 years	3	13 %
11 to 20 years	3	13 %
More than 20 years	17	74 %
Total	23	100 %
Background (multiple responses)		
Engineering	13	42 %
Economy	1	3 %
Business	5	16 %
Captain or chief engineer	10	32 %
Other*	2	6 %
Total	31	100 %
Number of newbuilding projects		
None	1	4 %
One to two	3	13 %
Three to five	7	30 %
Six to ten	3	13 %
More than ten	9	39 %
Total	23	100 %
Role in the newbuilding project		
Financial manager	0	0 %
Newbuilding manager	5	22 %
Technical manager	8	35 %
Purchase manager	0	0 %
Other**	10	43 %
Total	23	100 %

Project characteristics	Number of respondents (n=23)	Percentage (%)
Vessel type		
Offshore	3	13 %
Merchant	10	43 %
Passenger	0	0 %
Fishing	1	4 %
Other vessel types	9	39 %
Platforms and other floating objects		0 %
Total	23	100 %
Newbuilding project process		
The vessel was designed and built together with a customer (end user) for a specific tender	0	0 %
The vessel was designed and built together with a customer (end user) but without a particular project	3	13 %
The vessel was designed and built for a tender, but without the involvement of the customer (end user)	0	0 %
The vessel was designed and built together with a customer (end user) for a specific market segment and region	9	39 %
The vessel was designed and built for a specific market segment and region but without involvement of a customer	8	35 %
The vessel was built in speculation	2	9 %
Other***	1	4 %
Total	23	100 %
Newbuilding project operational strategy		
The vessel was designed and built to be owned, managed and operated by my company	12	52 %
The vessel was designed and built to be owned, managed but not operated by my company (Time charter)	1	4 %
The vessel was designed and built to be owned but not managed nor operated by my company (Bareboat)	1	4 %
The vessel was designed and built to be managed, operated but not owned by my company	7	30 %
The vessel was designed and built to be sold after delivery	2	9 %
Other	0	0 %
Total	23	100 %

*One of the respondents indicated that he or she was a naval architect.

**One participant was a vessel owner, another a ship operator, one more was managing director, two were consultants and one from chartering.

***Patrol vessel for a government.

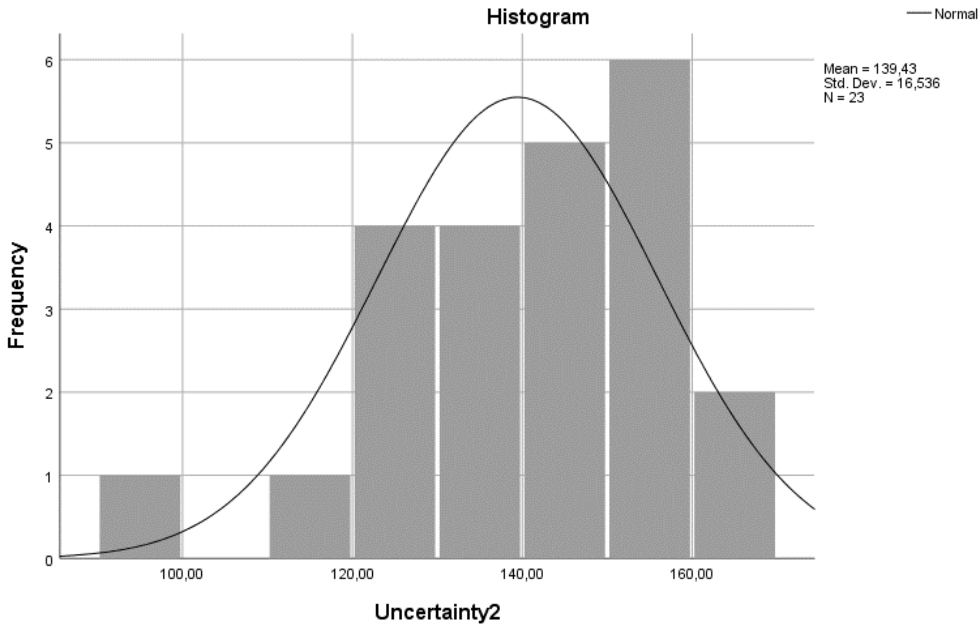
Appendix C – Data statistics

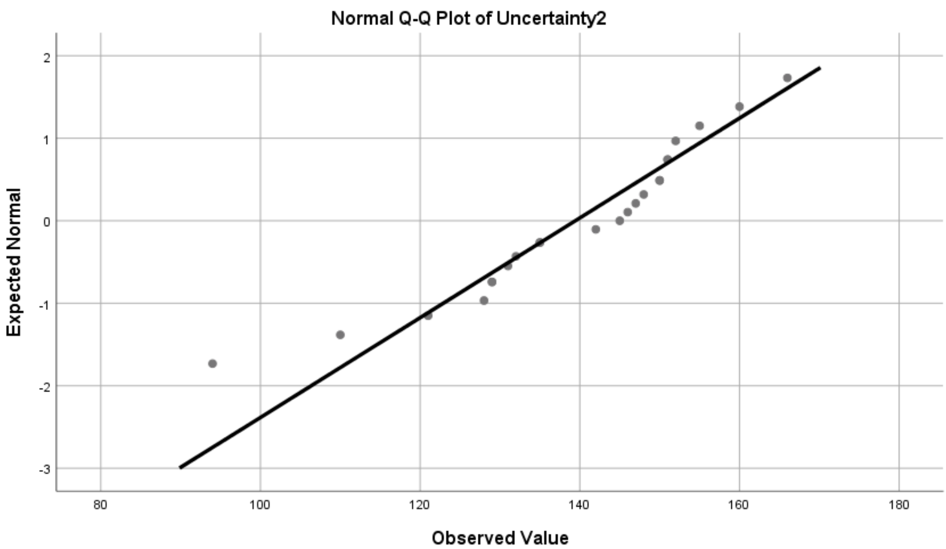
		Context		Agent		Input		Model		Process	
		Statistic	Std. Error	Statistic	Std. Error	Statistic	Std. Error	Statistic	Std. Error	Statistic	Std. Error
Mean		57.783	1.790	21.913	.869	15.565	.589	22.870	.879	21.304	1.068
95% Confidence Interval for Mean	Lower Bound	54.070		20.112		14.343		21.047		19.090	
	Upper Bound	61.496		23.715		16.787		24.692		23.519	
5% Trimmed Mean		58.374		21.959		15.628		23.097		21.145	
Median		61.000		22.000		16.000		24.000		21.000	
Variance		73.723		17.356		7.984		17.755		26.221	
Std. Deviation		8.586		4.166		2.826		4.214		5.121	
Minimum		37		14		10		11		12	
Maximum		67		29		20		30		34	
Range		30		15		10		19		22	
Interquartile Range		12		7		3		6		5	
Skewness		-1.009	.481	-.143	.481	-.466	.481	-.787	.481	.390	.481
Kurtosis		.044	.935	-1.017	.935	-.154	.935	1.509	.935	.735	.935

		DM_Rationality		Experience		Intuition		Decentralization	
		Statistic	Std. Error	Statistic	Std. Error	Statistic	Std. Error	Statistic	Std. Error
Mean		21.043	.636	19.739	.704	21.043	.789	14.348	.434
95% Confidence Interval for Mean	Lower Bound	19.724		18.280		19.407		11.448	
	Upper Bound	22.363		21.198		22.680		13.248	
5% Trimmed Mean		21.104		19.877		20.986		12.442	
Median		21		20		20		12	
Variance		9.316		11.383		14.316		4.328	
Std. Deviation		3.052		3.374		3.784		2.080	
Minimum		15		12		15		7	
Maximum		26		25		28		16	
Range		11		13		13		9	
Interquartile Range		6		4		5		2	
Skewness		-.287	.481	-.616	.481	.443	.481	-.842	.481
Kurtosis		-.779	.935	1.036	.935	-.596	.935	1.366	.935

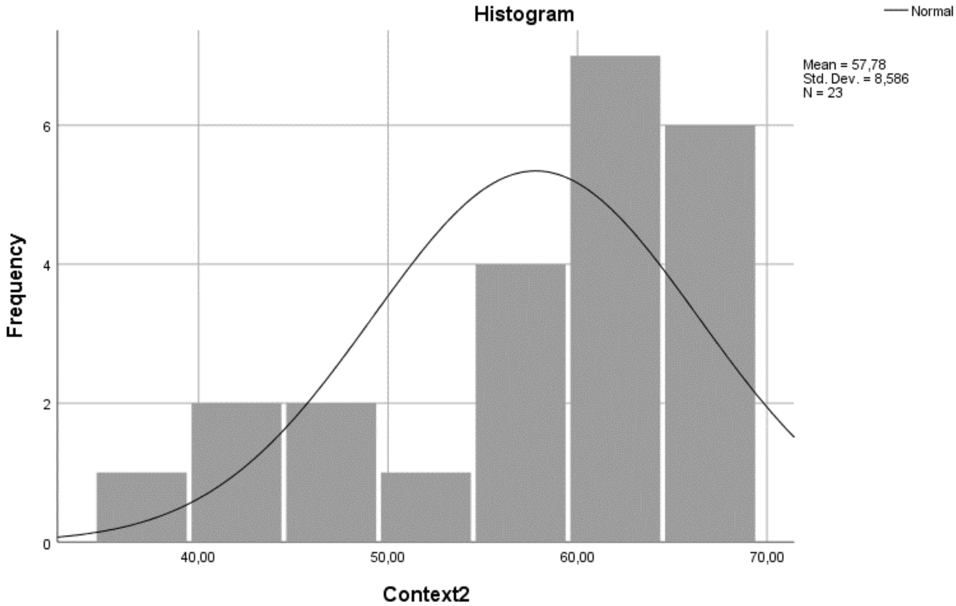
Appendix D – Response distribution

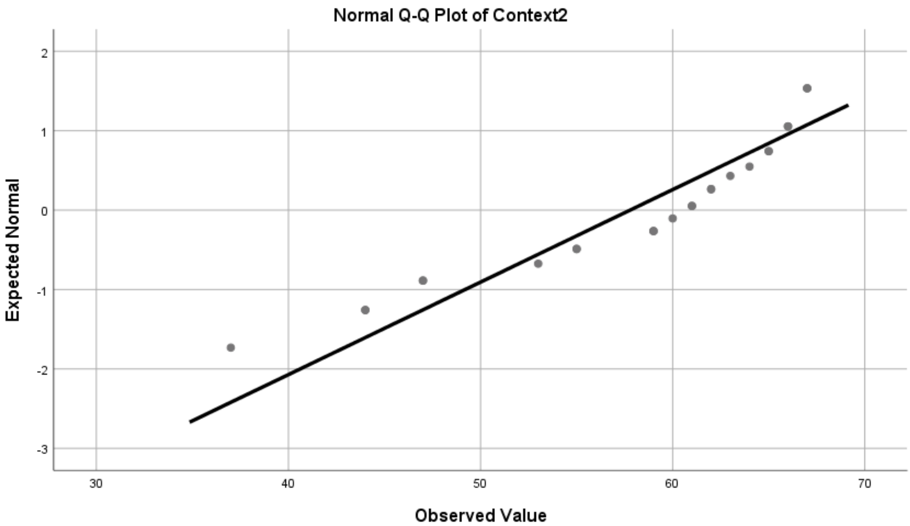
Uncertainty2 construct:



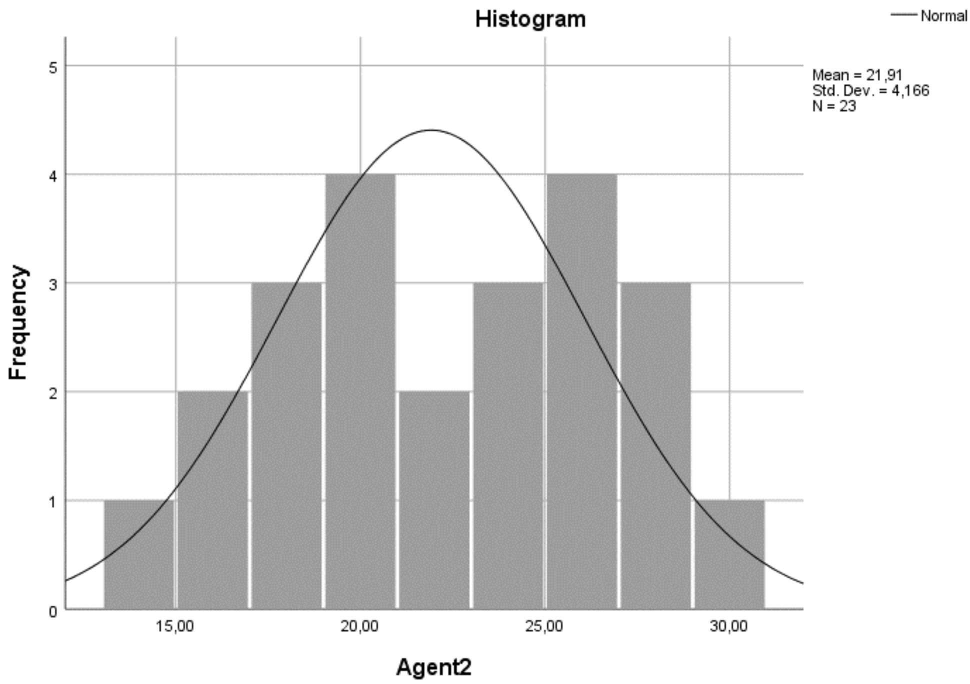


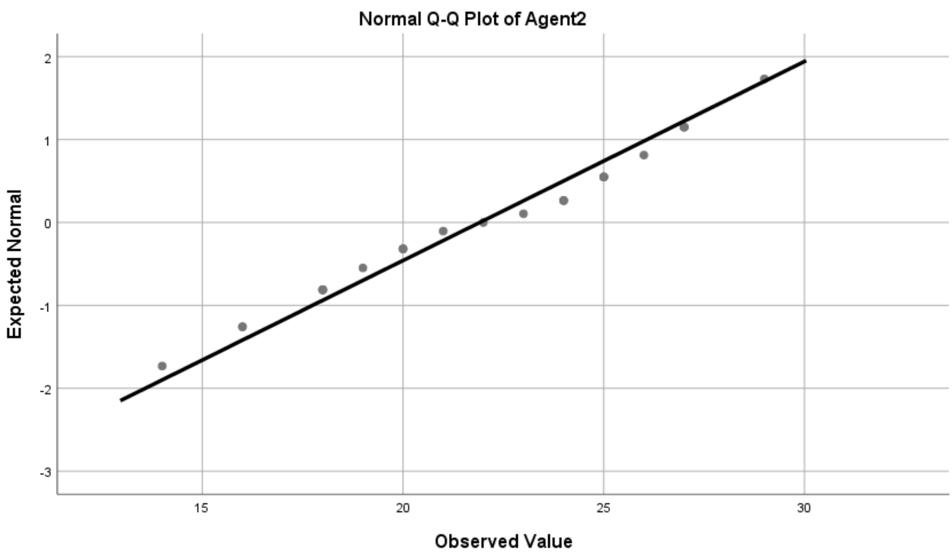
Context2 factor of uncertainty construct:



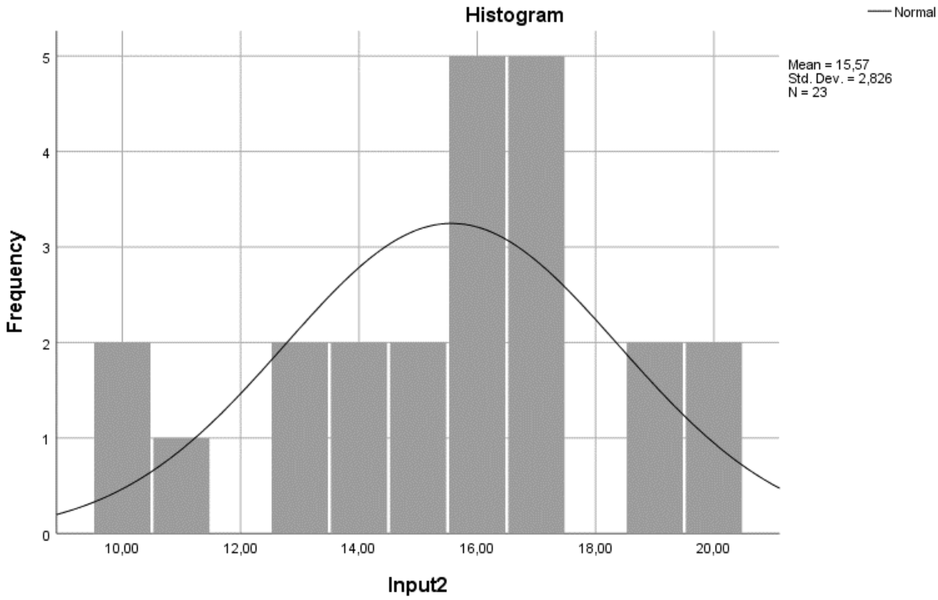


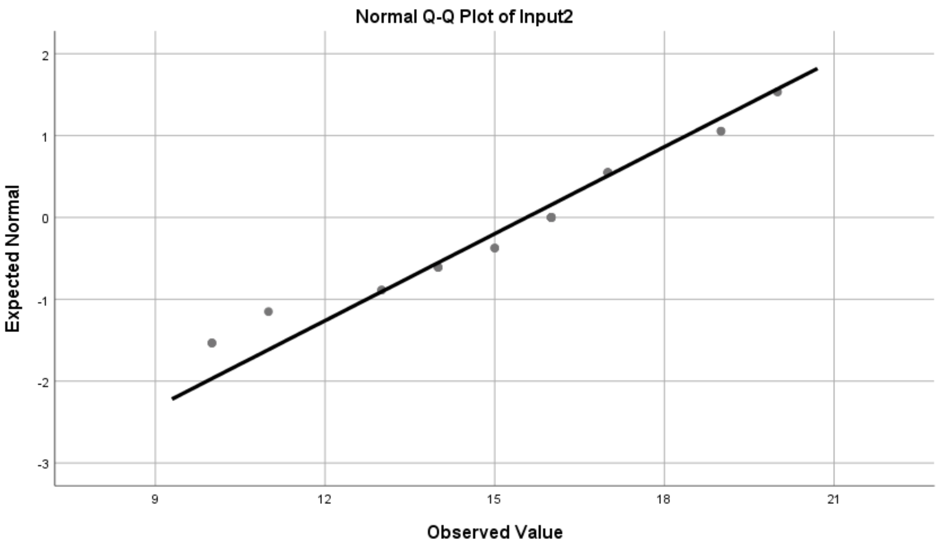
Agent2 factor of uncertainty construct:



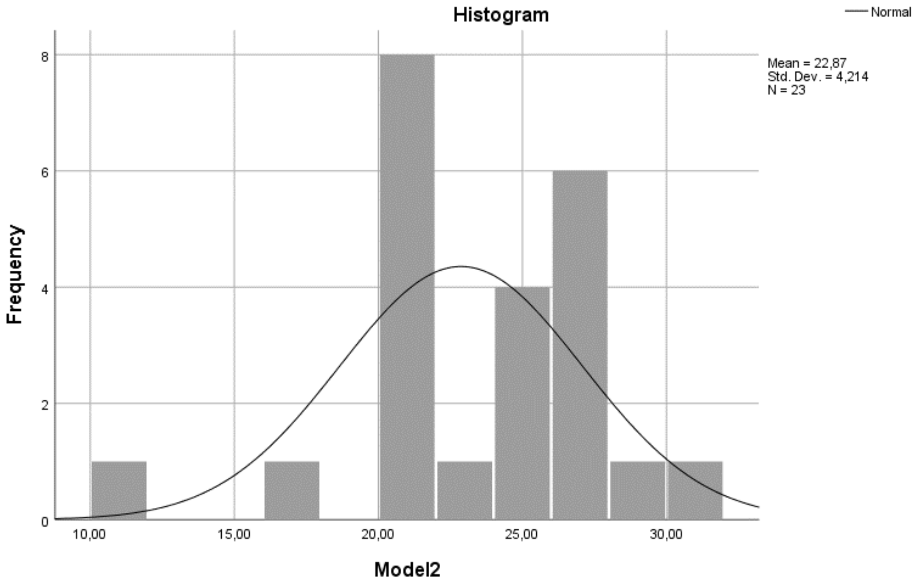


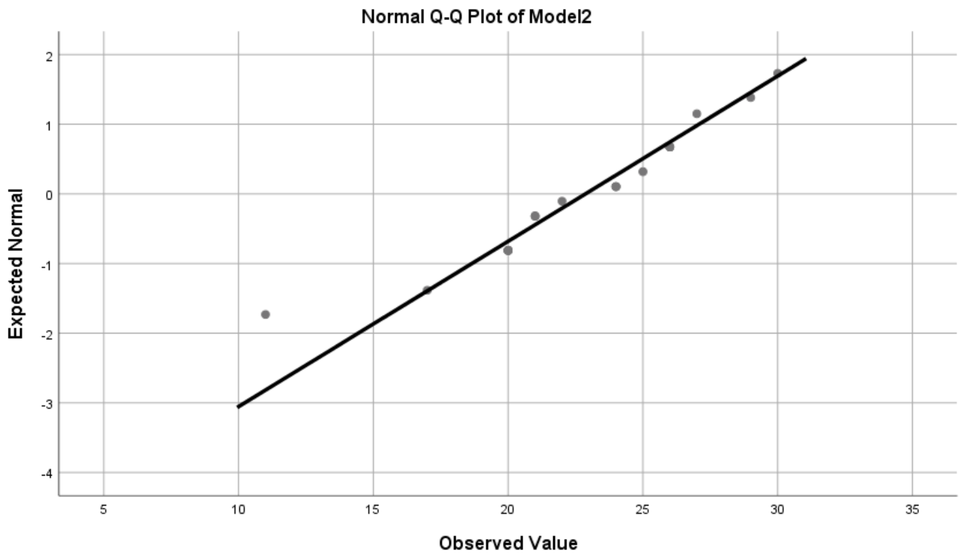
Input2 factor of uncertainty construct:



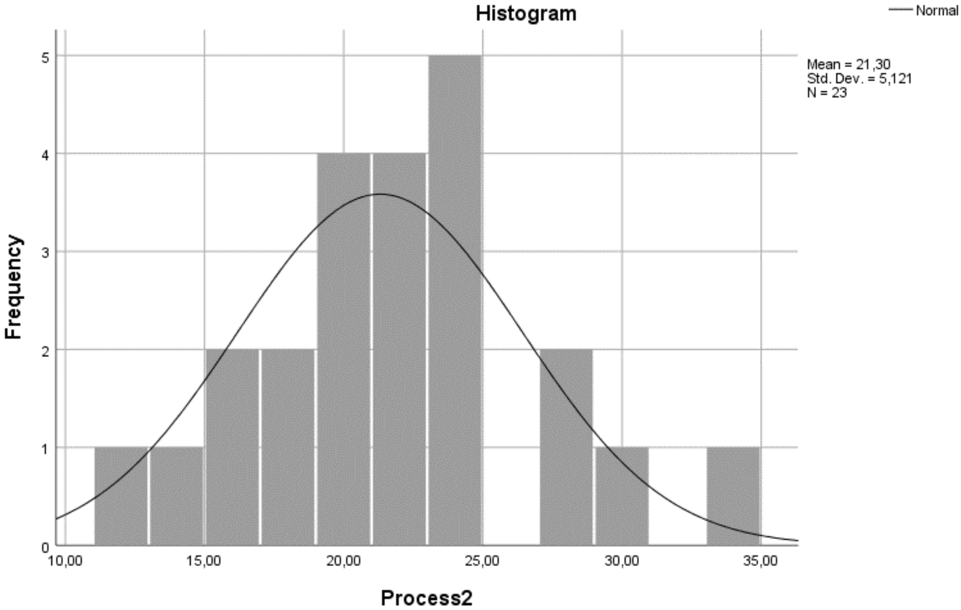


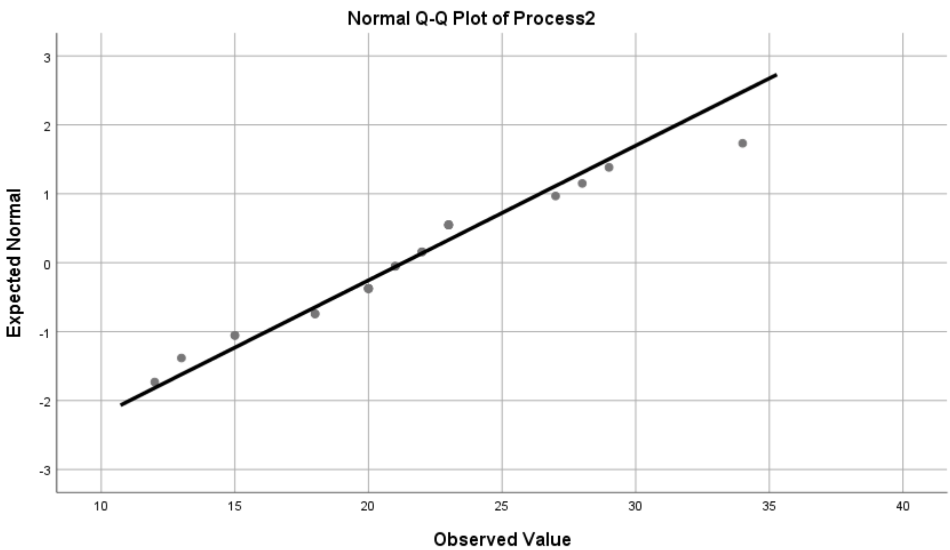
Model2 factor of uncertainty construct:



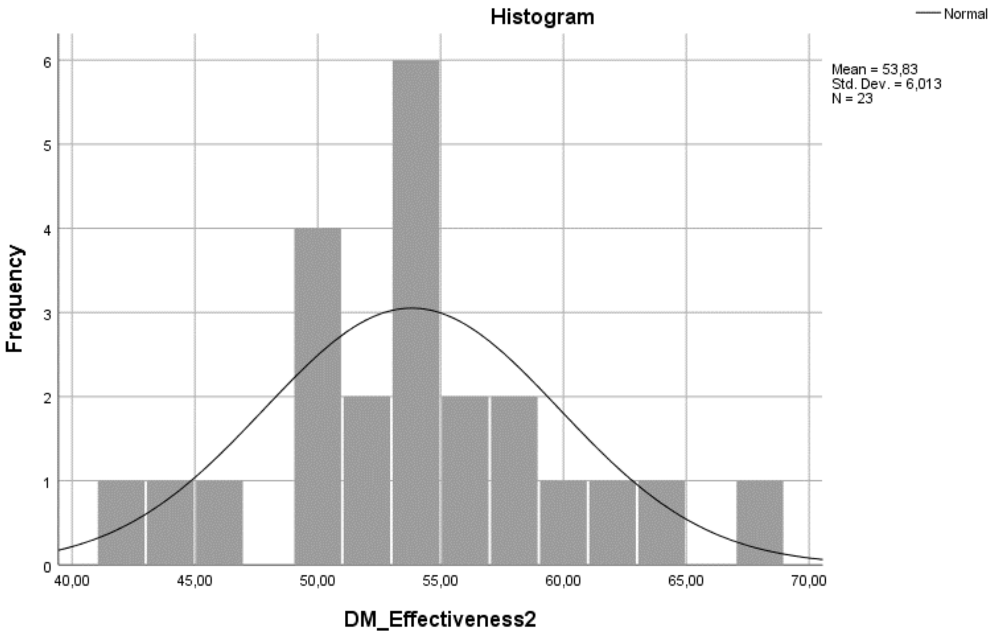


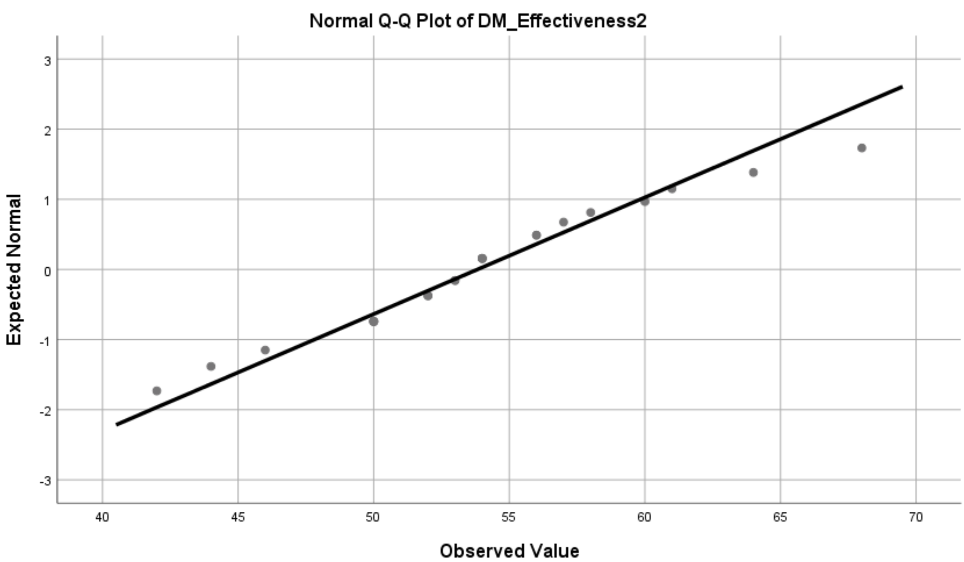
Process2 factor of uncertainty construct:



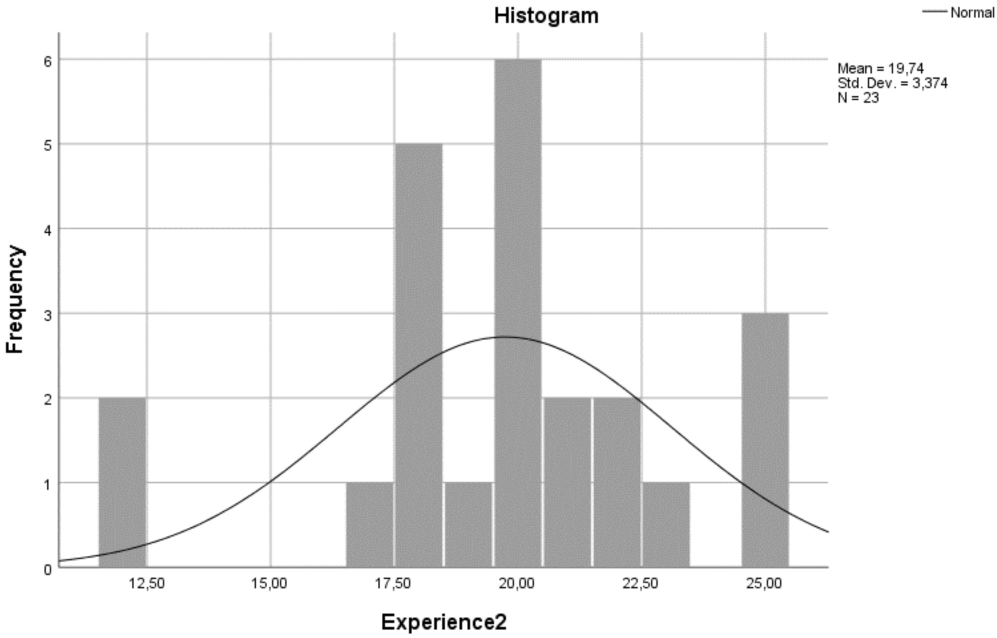


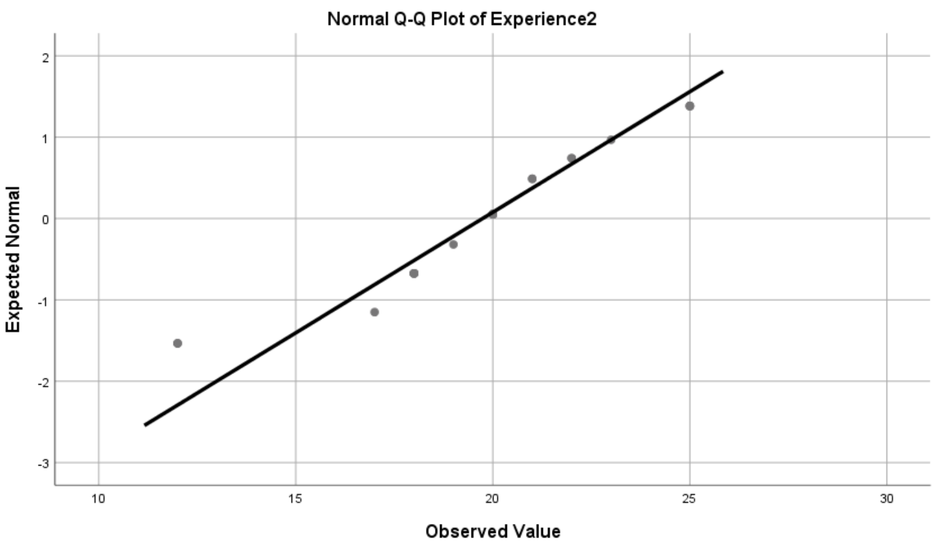
Decision-making effectiveness2 construct:



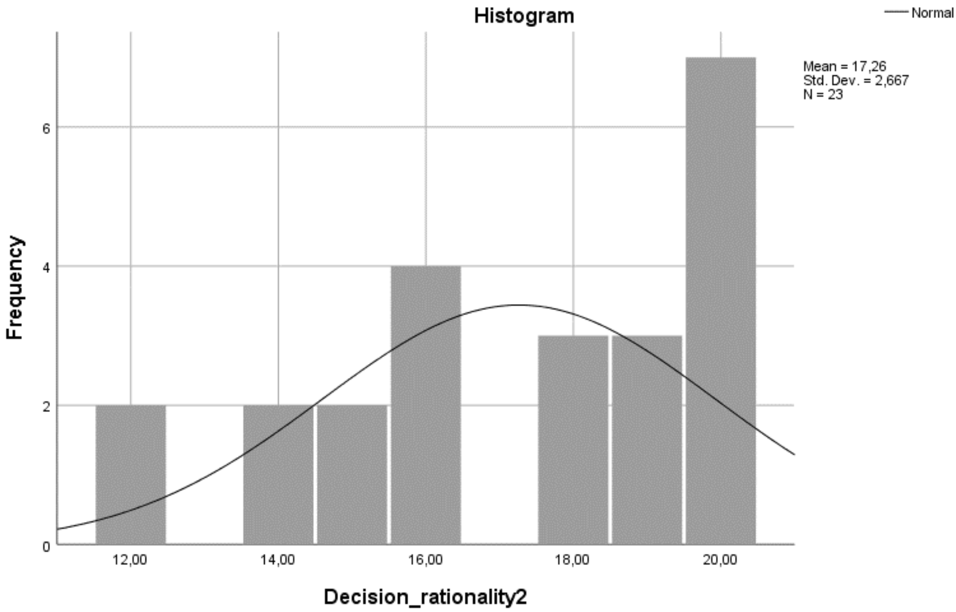


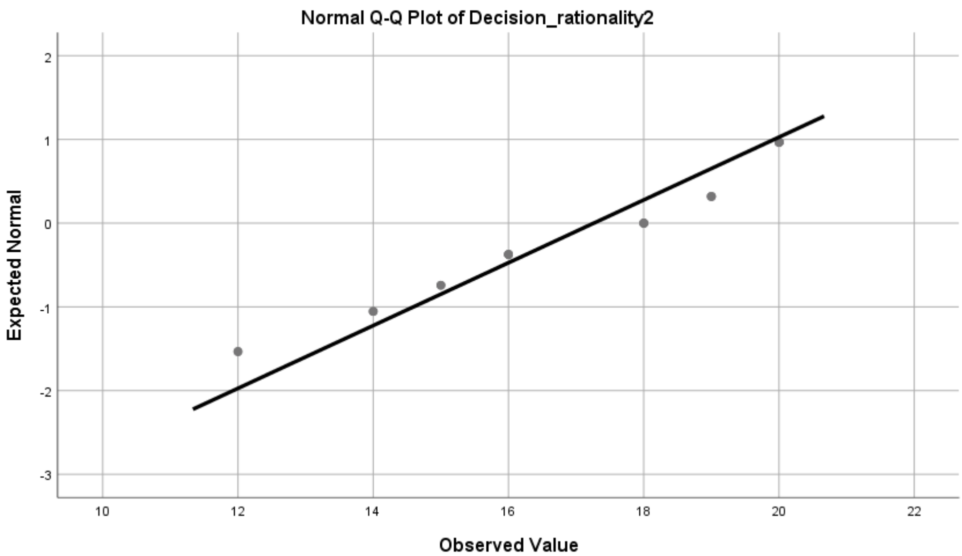
Experience2 factor of decision-making effectiveness:



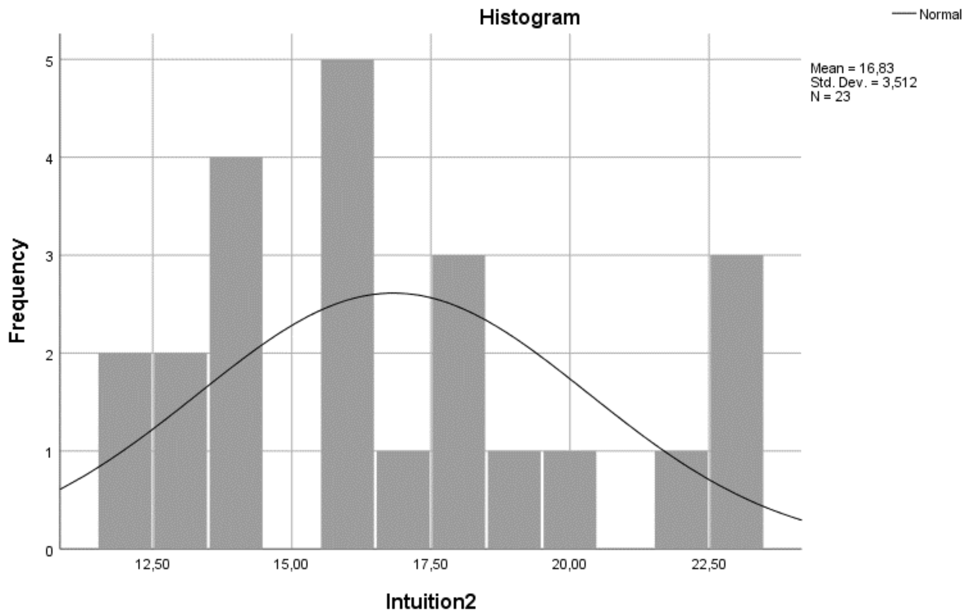


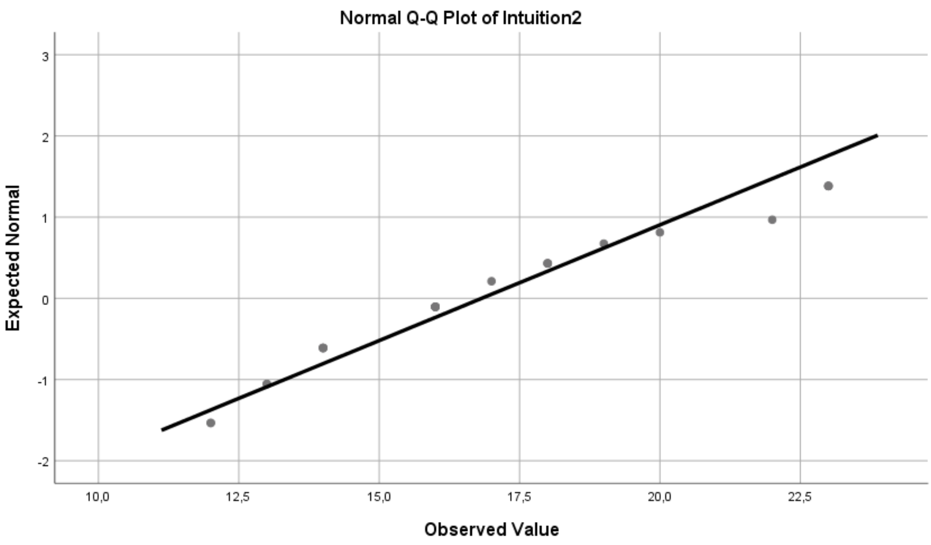
Decision rationality2 factor of decision-making effectiveness:



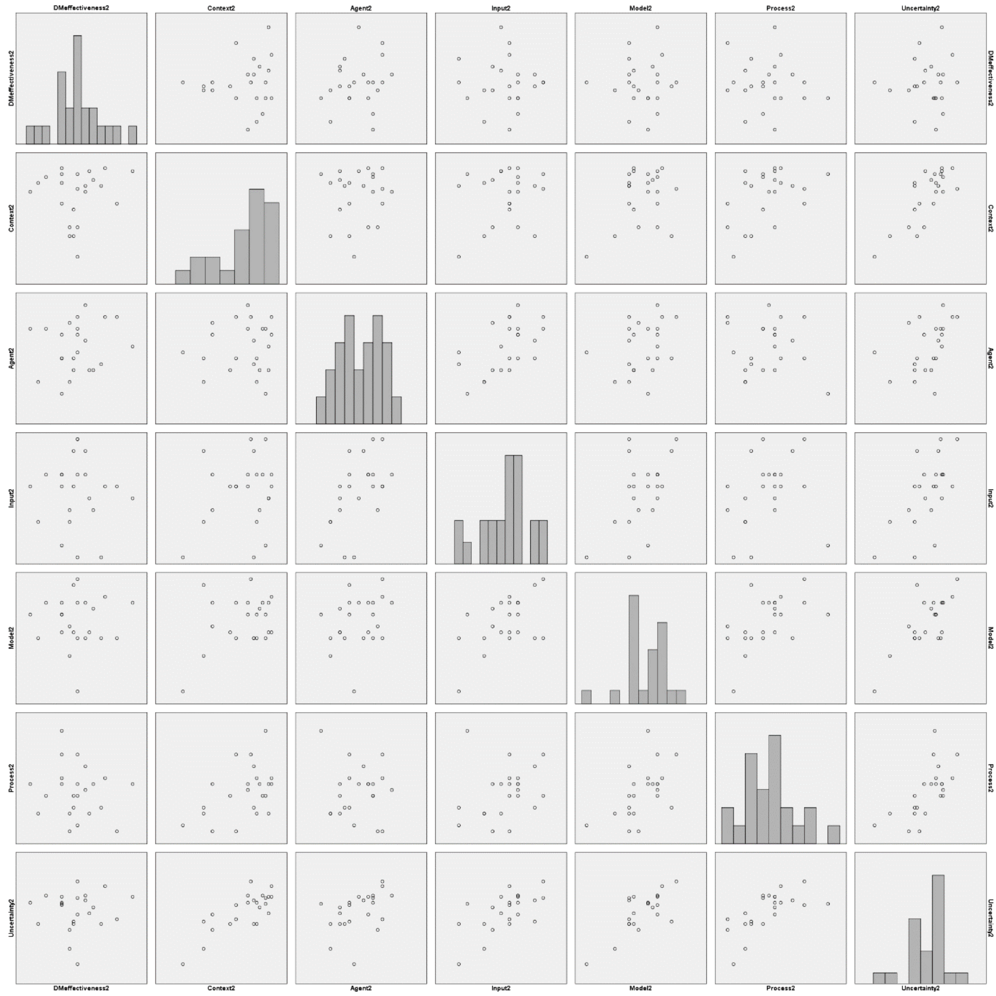


Intuition2 factor of decision-making effectiveness:





Appendix E – Correlation matrix plot



Appendix F – Main articles

Main article 1:

Sigurd S. Pettersen, Carl F. Rehn, Jose J. Garcia, Stein O. Erikstad, Per O. Brett, Bjørn E. Asbjørnslett, Adam M. Ross and Donna H., Rhodes, Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case, *Journal of Ship Production and Design*, 34 (1), 2018, pp.72-83.

Main article 2:

Jose J. Garcia, Sigurd S. Pettersen, Carl F. Rehn, Per O. Brett, Stein O. Erikstad and Bjørn E. Asbjørnslett, Overspecified Vessel Design Solutions in Multi-stakeholder Design Problems, *Research in Engineering Design*, 30 (4), 2019, pp. 473-487.

Main article 3:

Jose J. Garcia, Stein Ove Erikstad, Per Olaf Brett, The Value of Information in Conceptual Ship Design, submitted to *Ship Technology Research.*

Main article 4:

Jose J. Garcia, Per Olaf Brett, Stein Ove Erikstad, How Uncertainty Influences Decision-making Effectiveness in Conceptual Ship Design, submitted to *International Shipbuilding Progress*.

Main Article 1

Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case

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Abstract: *In this paper, we address difficulties in design of ill-structured commercial systems. We focus on issues related to evaluation of commercial system performance, involving perceptions of value, risk and time, to better understand trade-offs at the early design stages. Further, this paper presents a two-stakeholder offshore ship design problem. The Responsive Systems Comparison (RSC) method is applied to the case to untangle complexity, and to address how one can structure the problem of handling future contextual uncertainty to ensure value robustness. Focus is on alignment of business strategies of the two stakeholders with design decisions through exploration and evaluation of the design space. Uncertainties potentially jeopardizing the value propositions are explicitly considered using epoch-era analysis. The case study demonstrates the usefulness of the RSC method for structuring ill-structured design problems.*

Key words: Systems Design, Naval Architecture, Multi-Attribute Utility Theory (MAUT), Uncertainty, Complexity

1. Introduction

In a competitive maritime industry, there is a need to design, develop and deliver systems able to sustain value throughout a multi-decade lifetime. However, design of ocean engineering systems remains a difficult task, mainly due to the complexity and uncertainty governing these systems and their sociotechnical contexts. Even a clear definition of what is a better ship is ambiguous (Ulstein and Brett 2015) - it all depends. Understanding the relation between business strategies and corresponding marine design decisions, is not straight-forward, and the ship design task could be considered a wicked problem (Andrews 2012), or an ill-structured problem (Simon 1973). An ill-structured problem lacks a specified beginning and goal states, and the relation between these are unknown. More information must be gathered to enrich the problem definition and take informed decisions. A differentiation can hence be made between the problem of defining the problem to solve, and the problem of solving this problem. In this paper we stress the importance of understanding both of these aspects when it comes to design of complex systems.

The driving forces behind ocean engineering systems are often commercially oriented, introducing risks due to high market volatility. High oil prices and large ultra-deepwater discoveries have spurred the development of offshore oil and gas fields. Offshore construction vessels (OCVs) have taken part in this arena, particularly in the development of marginally profitable fields. More recently, the oil price collapse has had significant impact on this industry, rendering recent large multi-functional, *gold-plated* design solutions unprofitable. However, there are multiple other sources of contextual uncertainty that can affect the initial value propositions, and hence need to be considered in ship design, including technical, regulatory and operational factors. Risk and uncertainty are usually associated with negative consequences, but it is also important to acknowledge the upside opportunities uncertainty can introduce (McManus and Hastings 2006). Actively considering uncertainty in the design process can result in solutions that reduce downside risk and increase upside exposure, hence increasing the expected system performance over its lifetime. Design solutions that continue to provide value in a variety of contexts are known as *value robust* solutions, which can be achieved by either active or passive value robustness strategies, relating to whether the system actively can change in response to uncertainty or not. Active change involves implementation of changeability, characterized by the ability of a system to alter its form and function for the future. This involves system properties such as robustness, flexibility, agility, scalability and upgradeability, often also referred to as *ilities* (Fricke and Schulz 2005; Ross, Rhodes, and Hastings 2008; Niese and Singer 2014; Chalupnik, Wynn, and Clarkson 2013). The current situation in the offshore industry serves as a perfect example of the importance of focusing on value robustness and flexibility as key factors for success in a volatile industry.

Research on design of complex offshore engineering systems under uncertainty has recently gained momentum, as researchers have called for taking a broader view to engineering systems design processes (de Weck, Roos, and Magee 2011; Fet, Aspen, and Ellingsen 2013). With the current state of the offshore market, Erikstad and Rehn (2015) address the need for approaches for handling uncertainty in ship design. As a response to such calls, recent research within marine design focuses on novel methods, including methods from operations research and systems engineering (Garcia et al. 2016). Operations research methods include stochastic programming applied to issues in ship design like machinery selection under uncertainty (Balland et al. 2013; Patricksson and Erikstad 2016). Another recent approach uses Markov decision processes for evaluating ship design performance under uncertainty (Kana and Harrison 2017).

In this paper, we use the Responsive Systems Comparison (RSC) method to understand the decision making process in ship design. The RSC method is based on two systems engineering methods; i) multi-attribute tradespace exploration and ii) epoch-era analysis (Ross et al. 2009; Ross et al. 2008). Specific RSC applications include the design of an anchor handler tug and supply vessel (Gaspar et al. 2012), environmental regulation compliance in a lifecycle perspective (Gaspar et al. 2015), ship design for naval acquisition affordability (Schaffner, Ross, and Rhodes 2014), and a simplified offshore construction vessel (OCV) case (Keane, Brett, and Gaspar 2015).

The current paper explores the ship design process using the RSC method based on a real industrial case. It represents an analysis of the design of an offshore construction vessel for a joint venture of two stakeholders with different preferences. Following this, the most significant contribution are the theoretical insights to ill-structured design problems, and its formulation as a two-stage abduction process.

2. Evaluation of Commercial System Performance

Commercial engineering systems are typically selected on basis of economic decision criteria like net present value (NPV), or based on decision models allowing managerial flexibility, such as real options. A shortcoming of economic approaches is the number of assumptions one has to make. What are the future revenue streams? What are future market conditions? What discount rate should we choose? Microeconomic theory separates between risk averse, risk neutral and risk seeking behavior, normally assuming a risk averse attitude among stakeholders. This is not reflected in the use of NPV, or other economic measures of merit alone (Erichsen 1989; Benford 1970). Prospect theory (Kahneman and Tversky 1979) goes further, proposing that decision makers are loss aversive, and value losses as more negative than an equivalent win positively.

Value may vary over time, hence there are differences between the perceived value at the time of a decision and the value of that decision as actually experienced (Ross and Rhodes 2008). Investments in the commercial shipping industry are made in order to receive expected future benefits. Do we really know how to discount such perceived value? Empirical research in behavioral economics show that time inconsistent discount models, such as hyperbolic discounting, often account better for the preferences of stakeholders than the common assumption of time consistent discounting, as in financial NPV calculations (Frederick, Loewenstein, and O'Donoghue 2002). If we do not know which discounting model that best represents stakeholder perception of value, how can we then discount?

Taking future uncertainty into account in the cash flows by simulation based on historical data and extracting measures like value-at-risk, may help mitigate going into the *flaw of averages* (Savage 2009), but still does not take into account situations where a ship owner competes against other agents for different contracts, i.e. alternative, uncertain cash flows. Game theory may guide us some of the way, but it assumes that other agents act rationally. If agents are not rational, what is then the probability of winning a contract? What do the customers offering a contract actually care about when they select a specific bid among several? For complex systems facing uncertainty in their future operating context and in their perceived value to the stakeholder, economic decision criteria should be amended with other value attributes that better capture the things that stakeholders actually care about.

2.1. Profit as a subset of value

There are multiple examples of what may be perceived as value in commercial shipping today, in addition to profitability. Recently, there has been increased focus on environmentally friendliness. Several ship owners market themselves as "green". One may on the other hand, argue that for many profit-oriented players, green marketing is one way to increase profits further by making the product/service more attractive for customers and not because they care about the environment *per se*. However, it is difficult to reliably quantify the effect of this green marketing (Dahle and Kvalsvik 2016). It has also been proposed that the ultimate goal of some ship owners may be *prestige*, rather than pure profit. This may be signified by actions that drive costs, without really adding any "value" in economic terms. For example, 40% of platform supply vessels (PSVs) in the North Sea has been built with Ice Class, without really needing it (Garcia, Brandt, and Brett 2016). Again, it is possible to argue that ship owners believe this design choice will drive long-term profitability of their operation, as the vessel becomes more *versatile* with respect to operating region. These attitudes separate owners with a strong relation to the technical and operational aspects from ship owners with a purely commercial mind-set.

For commercial applications, in which profitability is the only objective, one may rephrase and say that profitability then is the (only) element of what the stakeholders perceive as value and success. Therefore, *value-focused thinking* (Keeney 1992) remains central, and value can hence be seen as a superset of profitability. If the preferred value attributes replicate profit-seeking stakeholders, this disaggregated approach nevertheless helps us untangle the complexity of the profit dynamics, which enables a better understanding of value trade-offs in various contextual settings.

2.2. Multi-attribute utility theory

Several methods for making decisions based on multiple value attributes exist (Ross et al. 2010; Papageorgiou, Eres, and Scanlan 2016). In this paper, we use multi-attribute utility theory, as presented by Keeney and Raiffa (1993). The attributes must adhere with the following criteria; i) *completeness*, representing all important aspects of decision making, ii) *operational*, possible to measure, iii) *decomposable*, so that they can be broken into parts for easier evaluation, iv) *non-redundant*, so that the same attributes are not counted twice, and v) *minimal*, so that the dimensionality of the problem is kept as small as possible. We here use an additive multi-attribute utility function, on the following form:

$$U(X) = \sum_{i=1}^{I} k_i U_i(X_i) \quad (1)$$

U here refers to the overall utility over all attributes. k_i are the weights for each attribute i, with an attribute value X_i. The value attributes selected for the model should be the things the stakeholders really care about, limited by short-term memory to seven, plus minus two (Miller 1956). Additional complexities can be handled by decomposition, making a value hierarchy adding structure to the utility function (Keeney 1992).

3. Methodology

The Responsive Systems Comparison (RSC) method is used in this paper. The RSC method was originally presented in Ross et al. (2009) and Ross, McManus, et al. (2008), but evolved to its current form in later papers, a recent reference being Schaffner et al. (2014). The stated purpose of the RSC method is "to take a designer or system analyst (RSC practitioner) through a step-by-step process of designing and evaluating dynamically relevant system concepts" (Ross et al. 2009). To fulfil this, the framework uses several other methods such as multi-attribute tradespace exploration (MATE) and epoch-era analysis (EEA). The RSC method is a generic approach to design decision making. A key heuristic for the method is to reduce the number of assumptions to a minimum. This makes it suited for combination with other tools and methods. Figure 1 illustrates the current layout of the RSC method, consisting of 9 steps clustered into 3 modules. Note that several feedback loops exist between the steps. As the understanding of the system increases, the stakeholders may perceive the system differently from their initial perspective.

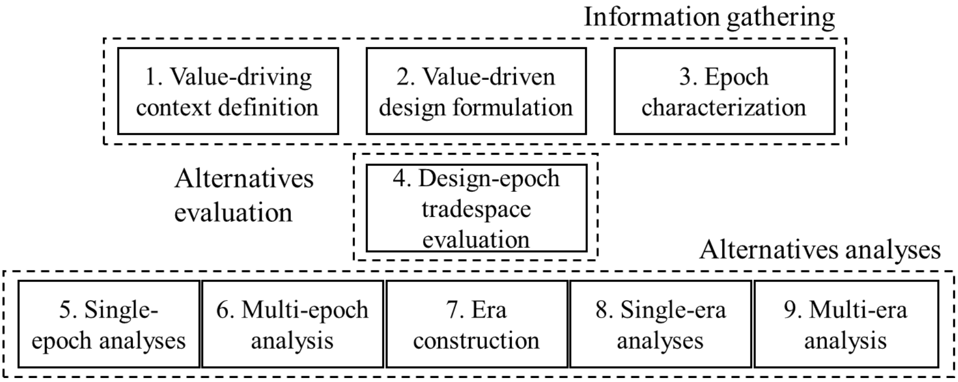

Figure 1: The Responsive System Comparison (RSC) method (adapted from Schaffner et al. (2014)).

The RSC method has been considered for implementation in this offshore case study due to its suitability to consider system design cases with changes in user needs and expectations, context and the system itself (Ross et al. 2009).

3.1. Information gathering

The initial steps of the RSC method collect the information used throughout the analysis. These steps should be supported by interviews with the decision-makers and other stakeholders in the project (Ross et al. 2009). First, in the "Value-driving context definition" the context of the system must be defined, in terms of how the context drives value. The "problem" in the environment is recast into an "opportunity", where an initial state can be turned into a desired state (Simon 1996). The outcome of the "Value-driving context definition" can be a value proposition. The value proposition will thus provide the link between the scope of the system design process and the business strategy of the stakeholders.

In the second step, "Value-driven design formulation", a set of value attributes are extracted from the value proposition. The attributes should be narrowed to the factors that stakeholders really care about. Having specified value attributes, the process of mapping from objectives and overall value statements to design descriptions can start. By abducting specific design instances and generalizing them into design variables that matter for system value, we map from the value space to the physical space driving costs (Ross, Rhodes, and Hastings 2008).

"Epoch characterization" is the final information gathering process where exogenous uncertainties are encapsulated within well-defined epoch variables. Every combination of epoch variables represents an epoch, a static short-run scenario. An epoch can be described as "a period of time for which the system has fixed context and fixed value expectations" (Ross and Rhodes 2008). Typically, epoch variables are technology or infrastructure changes, economic and market forces, policy and regulation, and resources and budgetary constraints.

3.2. Alternatives evaluation

The “Alternatives evaluation” defines the tradespace model upon which the designs are evaluated. The exact model which maps the connection between the value space, possibly via a performance space, to design and epoch spaces, is defined in this step. The modelling in this step relates to the causal mechanisms that were seen as “black box” in the information gathering. The aim of this evaluation process is to gain insight in how possible system architectures provide value, given important contextual uncertainties (Ross et al. 2009). The outcome of this stage are utility measures and costs for all design alternatives in all epochs. The required mapping between the value and design spaces is shown in Figure 2. In the figure, MAU refers to multi-attribute utility, while MAE refers to multi-attribute expense, a generalized cost representation.

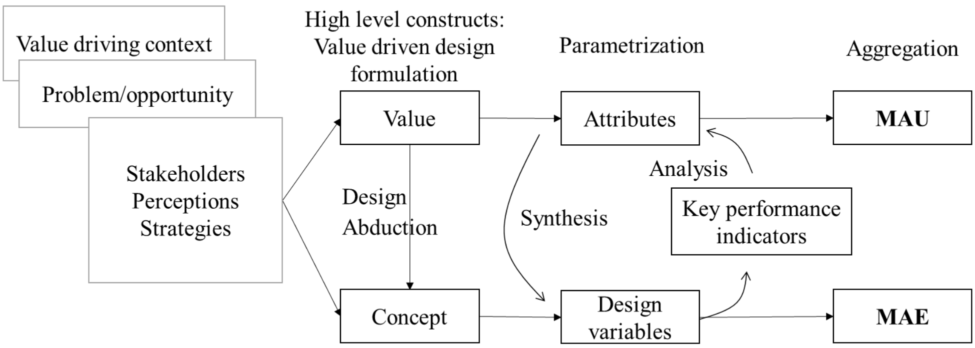

Figure 2: Relating value and design concept to the tradespace.

3.3. Alternatives analyses

“Alternatives analyses” consists of five steps concerned with producing metrics that let us compare and get insight of alternative designs in and across epochs and eras. In “Single-epoch analyses” tradespaces are explored with the Pareto efficient frontier of non-dominated solutions as the criteria of design goodness of fit (Keeney and Raiffa 1993). For the “Multi-epoch analysis”, Fitzgerald and Ross (2012) propose additional metrics to identify value robust designs across changing contexts and needs. These measures can be extended to consider active value robustness and changeability.

To be able to analyse design performance in a lifetime perspective, eras are constructed. Eras are scenarios representing the long run system context, consisting of sequences of epochs assembled along a timeline (Ross and Rhodes 2008). In accordance with microeconomics, the long run is signified by holding no factors constant (Varian, 2006). Era construction is an example of scenario planning, allowing for strategic planning for the medium to long-term, as they seek to answer from the stakeholder’s perspectives “What can conceivably happen?” and “What would happen if…?” (Lindgren and Bandhold 2003). Eras thus enable assessment of the lifecycle performance of various designs in different contextual operating conditions.

“Single-era analyses” and “Multi-era analysis” are the two final steps of the RSC method. In the “Single-era analyses” time-dependent effects of unfolding eras are investigated for interesting design alternatives (Schaffner, Ross, and Rhodes 2014). “Multi-era analysis” explores dynamic system properties by identification of patterns across multiple eras, exploring design-strategy pairs, to understand how we for example can implement changeability to ensure value robustness.

4. Case study

The case study centres on the design of an offshore construction vessel, following the RSC method. The information gathering phase was informed by interviews with decision-makers from a real ship design project, and a retrospective Accelerated Business Development (ABD) process. This process is described by Brett et al. (2006).

4.1. Step 1: Value-driving context definition

The business opportunity for a new offshore ship design emerges from a set of trends in the oil and gas industry. Increasing world population and economic growth is believed to lead to an increased demand for energy. While there are alternatives to oil and gas emerging, both due to the depletion of most easy-access resources and the threat of global warming, the offshore oil and gas markets are expected to be strong for a long time despite a characteristic high short-term volatility.

Two shipping companies form a joint venture to introduce novel offshore technologies to a new operational region. Their strategies and goals are different, while one provides a wide range of services within the Gulf of Mexico, the other is a world-wide operator with principal focus on light well intervention (LWI) services. The involvement of more than one key stakeholder increases intrinsically the difficulty of selecting a single design to build (Fitzgerald and Ross 2013). The merger of shared and competing goals into one system concept, calls for a collaborative engineering approach combining coordination, cooperation and collaboration between stakeholders. The intention of this approach is to attain more together than what would be possible apart. While the ship design project that results from the business opportunity is to be done by a joint venture between the two stakeholders, the preferences of each ship owner should be kept separate. This strategy makes it easier to understand which trade-offs and compromises are made through the decision-making process. For this reason, we keep the value propositions of each main stakeholder separate. The outcome of Step 1 is thus the two following value propositions:

> **Stakeholder 1:** *“Being the first subsea contractor in the Gulf of Mexico by building and operating a fleet of profitable OCVs.”*
>
> **Stakeholder 2:** *“Being the leading provider of high quality solutions for the offshore oil industry, by adding advanced, environmentally friendly and profitable OCVs to the existing fleet.”*

4.2. Step 2: Value-driven design formulation

Once the value-driving context has been defined, which helps us outline the problem to be solved, we can start formulating the value-driven design. The value attributes are derived from the value propositions, and therefore align with the business opportunity that was identified in Step 1. Interviews with key decision makers are an important ingredient when collecting the appropriate statements of needs, and expressing them in terms of objectives (Ross et al. 2009). We separate between monetary and non-monetary aspects of value, which are assessed independently in the model, due to their temporal differences. Profitability is incorporated indirectly in the model, through cost minimization for feasible designs for a mission with a given rate, and is considered a value attribute at the era level. See Chapter 4.4 and Chapter 5.2 for further information and discussions on profitability. The non-monetary value attributes of the two key decision-makers are at the epoch level, and are summarized in Table 1. The associated single-attribute utility functions for the non-monetary value attributes of each stakeholder are given in Figure 3.

Table 1: Stakeholder value attributes.

Stakeholder	Value att.	Level	Units	Worst	Best	Description
1	Originality	Epoch	[-]	0	10	First mover with advanced equipment
1	Replicability	Epoch	[-]	0	10	Easiness to replicate at different yards.
1	Profitability	Era	[$]	-	-	Net cash flow from the investment.
2	Eco-friendliness	Epoch	[-]	0	10	Environmental friendly transit and
2	Fleet	Epoch	[-]	0	10	Integrability with current advanced
2	Profitability	Era	[$]	-	-	Net cash flow from the investment.

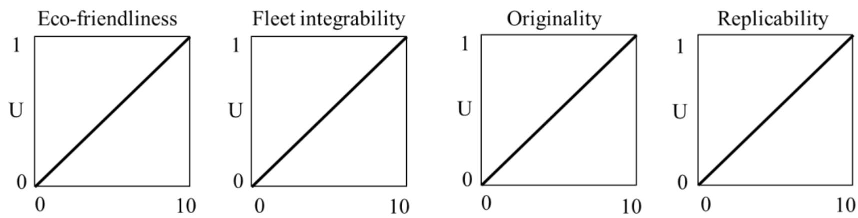

Figure 3: Single-attribute utility functions.

Originality represents the ability of being the first mover with advanced equipment into the Gulf of Mexico (GoM) market. Originality is a measure of how technically advanced a vessel is compared with the current operational fleet in this area, physically operationalized through the crane lifting and light well intervention capability on a scale from 0 to 10 where higher is better. Replicability represents a measure on the simplicity to which a design can be reproduced by another yard. It reflects the building complexity, in this maritime context operationalized by the gross tonnage (GT) on a defined 0 to 10 scale, where a lower GT represents a higher number on the scale. Complex ships are assumed to be more difficult to copy and reproduce compared to simpler ones, as more information is needed to describe complex systems. Eco-friendliness represents the ability of a design to perform with as low environmental footprint as possible. This is defined on a scale from 0 to 10, dependent on aspects of eco-friendliness of a design in transit and operation operationalized through the water resistance of the design and the fuel type used. Fleet integrability represents the degree to which the design integrates into the current advanced light well intervention fleet of stakeholder 2. The attribute is defined on a scale from 0 to 10 based on the LWI capability of the current fleet of stakeholder 2.

Table 2 presents the design variables generalized from common parametrizations of offshore vessel designs. The design variables represent the aspects of the physical design concepts with stronger influence on the value attributes. To avoid disregarding a-priori designs of high potential value, we do not check for basic feasibility requirements at this stage, like stability or minimum freeboard.

Table 2: Design variables.

Design variable	Units	Values
Length	m	[120, 140, 160, 180]
Beam	m	[20, 25, 30, 35]
Depth	m	[8, 11, 14]
Installed power	MW	[5, 10, 15, 20, 25]
Accommodation	persons	[50, 150, 250, 350]
Main crane capacity	tonnes	[0, 200, 400, 600, 800]
Light well intervention	tonnes	[0, 300, 600]
Moonpool	[-]	[No, Yes]
Fuel type	[-]	[MGO, Dual Fuel (DF)]
Dynamic positioning	[-]	[DP2, DP3]
Remotely operated vehicle	[-]	[No, Yes]

4.3. Step 3: Epoch characterization

The epoch characterization phase elicits exogenous uncertainties perceived by the stakeholders as potentially impacting the value of the system. For the offshore vessel in this case study, we define the system boundary around the ship itself, and hence eight epoch variables are predicted to affect the vessel, as illustrated in Figure 4.

Figure 4: Ship system boundaries and epoch variables.

The eight epoch variables, classified in contract parameters and technical requirements are presented in Table 3. Additionally, we define each of the four operational areas as a combination of water depth and sea state, represented by the significant wave height (Hs), as described in Table 4. Further, the possibility that the ship is in lay-up is also included.

Table 3: Epoch variables representing important sources of exogenous uncertainty.

	Epoch variable	Unit	Values
Contract parameters	Contract rate	k$/day	[50, 70, 120, 170, 220]
	Operational area	[-]	[1, 2, 3, 4]
Technical requirements	Light well intervention req.	tonnes	[0, 300, 600]
	Module weight req.	tonnes	[0, 200, 400, 600]
	Accommodation req.	POB	[50, 150, 250, 350]
	ROV req.	[-]	[0, 1]
	Dynamic positioning req.	[-]	[0, 1]
	Deck area req.	m^2	[0, 1000]

Table 4: Characteristics of depth and sea state (Hs) for the four operational areas.

Operational area	Epoch var. value	Depth [m]	Hs [m]
Gulf of Mexico	1	1600	2.0
Brazil	2	2500	2.5
North Sea	3	200	3.0
West Africa	4	1800	1.0

4.4. Step 4: Design-epoch tradespace evaluation

This step enables the representation of all designs from the design space in terms of utility and costs in the tradespace, to gain an understanding of how system concepts provide value given important contextual uncertainties (Ross et al. 2009). At this stage, we model the mapping between the value space and the design space. Some of this mapping takes place by going through modelling of physics and economics, via "key performance indicators" (KPIs). The outcome of Step 4 is a measure of multi-attribute utility (MAU), and a cost measure, multi-attribute expense (MAE).

There are various intermediate performance indicators in the model, which are central in the mapping between value and physical design. At an early design stage, we want to evaluate multiple designs in different epochs, hence the models need to be low fidelity in order to make it computationally feasible. Therefore, in absolute terms, the estimated properties may not be correct, but for comparisons in relative terms indicate the main relationships between the relevant parameters. The physical calculations include lightweight, deadweight, deck area, speed, acquisitional and operational costs.

This paper focuses on design of commercial systems, where profitability is central. It is important to understand that even though profitability is not assessed as a value attribute in a particular epoch, it is incorporated indirectly because we want to minimize the costs in a mission with a given day rate. Hence, when we seek Pareto optimal designs, we also find the designs that maximize the profitability for each epoch, and this way of structuring the problem opens up for easy exploration of the trade-off between profitability and other value attributes such as eco-friendliness. In order to assess profitability, a financial model is used to calculate the cash flows. The financial system boundary is around the ship itself, and hence we do not include financial details on the fleet level for the ship owners. Fuel costs are not included in this model, since they are assumed paid by the charterer. The system boundary in this analysis does not include specific aspects of the market, such as supply and demand, and we hence just work with contracts, with their rates and requirements. Assessment of these underlying dynamics remains outside the scope of this analysis.

Figure 5 illustrates the architecture of the methodological approach in this paper, comprising mainly four elements: the design space, the system modelling, the epoch space and the resulting evaluation criteria: value and cost. What is particularly important to consider, is how an epoch can be decomposed into information regarding the context and needs. Both, context and needs may change over time, randomly, or one may see more casual relationships. Proper investigation of these dynamics is important in order to make value robust design decisions, for example through interviews with the stakeholders. In this analysis, we assume that the set of value attributes remains constant in different epochs. Further, in the process of calculating the MAU, we assume that the weights remain static at 0.5 for each of the two value attributes for each of the two stakeholders. The different costs components are aggregated to a multi-attribute expense (MAE) function for each stakeholder, where acquisition costs and operational costs are weighted equally. When a design does not satisfy the requested technical requirements in an epoch, it is considered infeasible. No direct limitations are imposed on the newbuilding price.

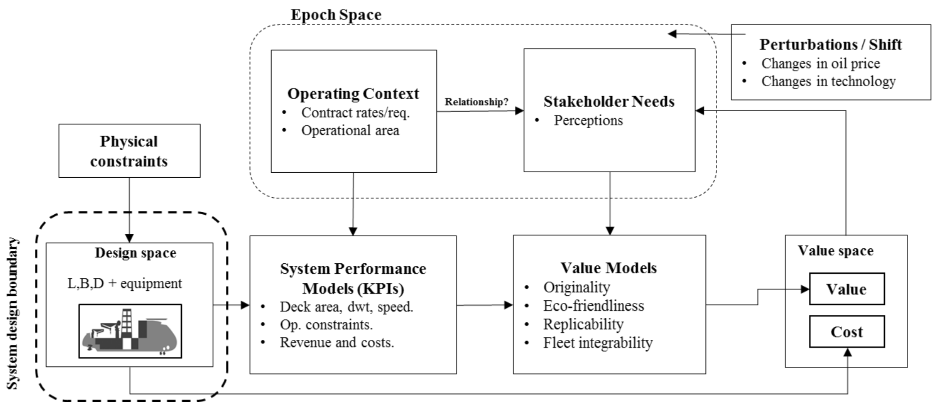

Figure 5: Illustrating the design-value mapping model.

Once the value-epoch model is defined, all design solutions can be plotted in terms of MAU versus MAE, creating a tradespace for a given epoch. Taking the view that we investigate a trade-off between utility and cost, the non-dominated solutions become those designs that for each possible budgetary constraint maximizes utility. Since we maximize utility and minimize costs for a given contract with a given day rate, we indirectly find the designs that maximize the profit for that particular epoch and contract.

Table 5: Sample designs for further assessment.

Design name		I	II	III	IV	V	VI
Design ID	[-]	116454	114843	110835	128020	111081	128356
L, B, D	[m]	140,25,8	160,30,11	160,20,8	180,20,8	120,30,8	180,20,8
Main crane	[tonnes]	200	400	800	400	800	800
Accommodation	[POB]	150	250	150	150	250	250
Engine power	[MW]	15	25	15	15	15	15
Light well intervention	[tonnes]	300	0	600	600	600	600
Moonpool	[-]	Yes	Yes	No	No	No	No
Fuel type	[-]	Diesel	Diesel	Diesel	DF	Diesel	DF
Remotely operated vehicle	[-]	Yes	Yes	Yes	Yes	Yes	Yes
Dynamic positioning	[-]	DP3	DP3	DP3	DP3	DP3	DP3
Deck area	[m^2]	1200	2000	1000	1300	1000	1000
Dwt	[tonnes]	7300	19000	4500	6700	5400	5400
Max speed	[knot]	18	20	18	18	17	18
Acquisition cost	[m$]	164	210	215	236	223	247

To gain better insight in this design problem, six designs are studied more in detail in the following analyses, as illustrated in Table 5. Since we do not check for technical feasibility on the design variables, to reduce the number of assumptions, we may get solutions that seem unrealistic to ship designers. This is especially true for designs III and IV.

4.5. Step 5: Single-epoch analyses

In this step, we analyze and explore the tradespaces for each stakeholder in different epochs, gaining insight into the trade-offs among alternative designs. This process is carried out with the means of learning about the complex system behavior in different static contexts. Tradespace yield is a useful metric for evaluating single epochs, which takes the feasible designs within the epoch, as the percentage of the total number of enumerated designs (Ross et al. 2009). This also gives a hint of whether the attribute ranges should be redefined to make it easier for designs to fulfil requirements. For illustration, we assess the system behavior under three epochs, represented in Table 6.

Table 6: Three relevant example epochs for the Gulf of Mexico.

	Low case	Base case	High case
Epoch ID	981	6813	6889
Contract rate	$70 000/day	$170 000/day	$220 000/day
Operational area	Gulf of Mexico	Gulf of Mexico	Gulf of Mexico
LWI	0 tonnes	600 tonnes	600 tonnes
Module weight	200 tonnes	200 tonnes	400 tonnes
Accommodation	50 people	150 people	250 people
ROV req.	Yes	Yes	Yes
Dynamic positioning	DP2	DP3	DP3
Deck area req.	0	1000	1000
Tradespace yield	0.20	0.02	0.01

The tradespace yield measures are in this case identical for the two stakeholders. Only the designs that have the technical equipment to satisfy the requirements in an epoch are defined as feasible. Due to the structure of the model, and the high number of designs generated, the tradespace yield measures becomes relatively low.

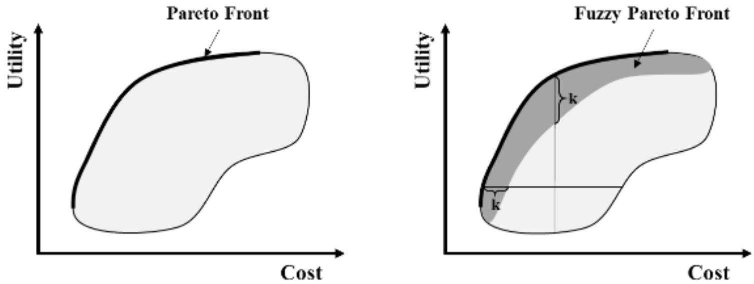

Figure 6: Pareto optimality and Fuzzy Pareto optimality with k% fuzziness, for a tradespace defined by utility and cost.

There exist multiple metrics to measure the performance, mostly based on Pareto efficiency. Figure 6 demonstrates the concept of the Pareto efficient frontier, with and without fuzziness, as introduced by Smaling and Weck (2004). The Fuzzy Pareto Number (FPN) is a metric that can be used to quantify the distance to the Pareto front for each design. FPN is defined as the smallest fuzziness percentage for which a design is in the fuzzy Pareto set (Fitzgerald and Ross, 2012). The FPN of the six designs followed in this analysis for both stakeholders are illustrated in Table 7. FPN of 101 represents infeasibility, while FPN of 0 stands for Pareto optimality.

Table 7: Fuzzy Pareto Number (FPN) for the six designs in three considered epochs for stakeholder 1 and 2.

	Stakeholder 1			Stakeholder 2		
Design	Low case	Base case	High case	Low case	Base case	High case
I	101	101	101	101	101	101
II	22	101	101	16	101	101
III	3	0	101	4	1	101
IV	8	8	101	0	0	101
V	5	3	0	9	6	2
VI	7	3	0	0	0	0

4.6. Step 6: Multi-epoch analysis

The purpose of multi-epoch analysis is to find value robust systems across changing contexts and needs, by measuring system value across multiple epochs. A separation can be made between actively and passively value robust systems (Ross, Rhodes, and Hastings 2008):

- **Passively value robust** systems are relatively insensitive to changing conditions, and continue to deliver value above an acceptable level, while maintaining the initial design configuration.

- **Actively value robust** systems can benefit from dynamically taking actions in response to changing conditions that may deteriorate the system performance, such as implementation of changeability.

In this analysis, we only consider passive value robustness. An overview of metrics for assessing design performance across multiple epochs is presented by Fitzgerald and Ross (2012). The Fuzzy Normalized Pareto Trace (fNPT) identifies passively value robust designs. In its "unfuzzy" form (0% fuzziness), it is simply the fraction of epochs in which a design is located on the Pareto front. With a fuzziness above 0, it represents the fraction of epochs in which the design is within the fuzzy Pareto set. If active value robustness is achieved through changeability, *effective* fNPT may be used as a measure of improved performance. The feasible design space is changing in size for each epoch. The fNPT metric is assumed only based on the feasible designs in an epoch.

Table 8: NPT and k% fNPT for the six designs for stakeholder 1 and 2.

		Stakeholder 1			Stakeholder 2		
Design	Feasible	NPT	10% fNPT	20% fNPT	NPT	10% fNPT	20% fNPT
I	0.06	0.00	0.02	0.06	0.00	0.03	0.06
II	0.07	0.00	0.00	0.00	0.00	0.00	0.00
III	0.35	0.01	0.34	0.35	0.00	0.27	0.35
IV	0.17	0.00	0.01	0.14	0.00	0.17	0.17
V	0.45	0.00	0.31	0.44	0.00	0.04	0.33
VI	0.45	0.00	0.27	0.44	0.00	0.44	0.45

The passively value robust metrics are relatively low due to the structure of the problem. There are no static designs that perform well over all the epochs considered. Large multi-functional vessels will be able to take different missions, but require higher rates to be profitable than smaller designs that are optimized for single missions. This reasoning indicates that changeability could be valuable. For a proper assessment of the active value robustness of the designs, weighting and filtering based on probability may be considered.

4.7. Step 7: Era construction

The entire era space for this problem would be extremely large, considering the sizeable epoch space. While simulation methods could be applied to sample eras based on historical data following simple logical rules, a narrative approach is here used to represent likely system lifecycle scenarios. This enables simple "what if"-analyses that are easily communicated among stakeholders. Epoch durations through an era could be dynamic, but in this case we simplify and assume a static time span of 1 year per epoch. This intends to capture the volatility of the oil and gas industry, and to include the possibility for shorter "accident-driven" missions. For the case, the following three eras are specified for a 20-year system lifecycle, encapsulating stakeholder beliefs. The three eras are presented in Figure 7, in terms of operational areas, types of operation, day rates and technical requirements. Era I represents a baseline scenario, with an initially targeted tender contract and a strong offshore market continuation. Era II represents a similar start with the targeted tender contract, followed by a weakened market ending with offshore decommissioning in later years. Era III represents a market collapse where the initial targeted tender contract is not won.

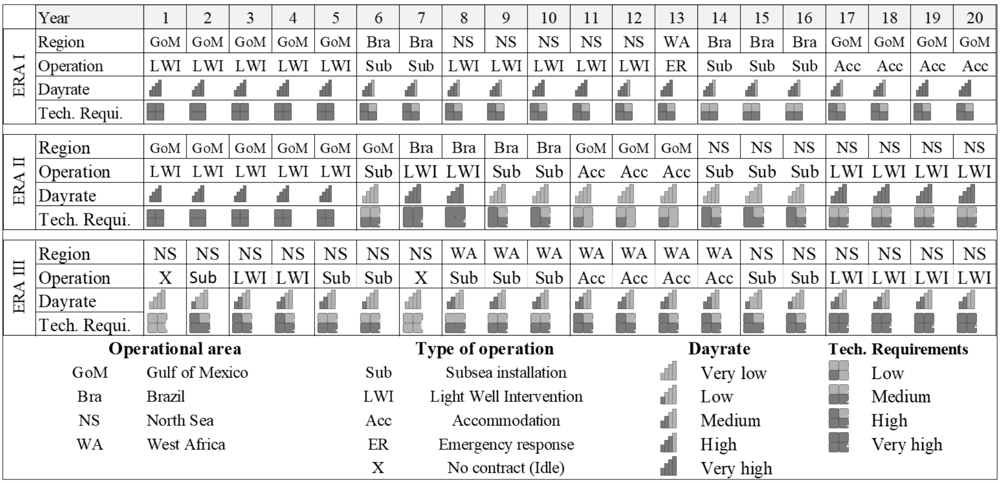

Figure 7: Description of three narrative eras.

4.8. Step 8: Single-era analyses

Single-era analyses focus on long-term value sustainment through dynamic scenarios with changing contexts and needs. Insight is gained through investigation of time-dependent effects that emerge through various sequences of epochs. For passively value robust designs, one can better identify strengths and weaknesses for different eras, and understand value trade-offs in various realizations of the future. For actively value robust designs, long run strategies can be examined as means to exercise changeability, and identify path dependencies. Visualization of these datasets remains difficult, but is an essential tool for gaining insights and communicating the results to stakeholders (Curry et al. 2017). Figure 8 illustrates an interactive map of the performance of various designs in the three narrative eras constructed in this case.

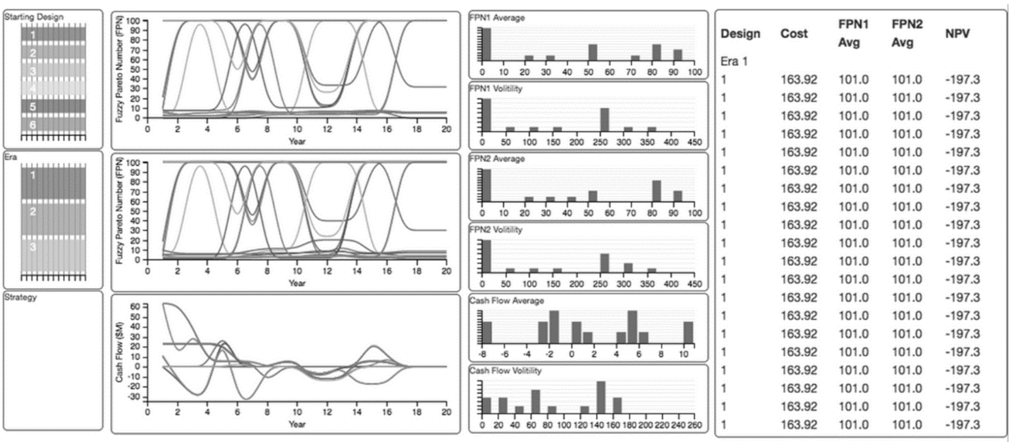

Figure 8: Illustration of candidate designs over different single eras with supporting metrics (adapted from Curry et al. (2017)).

Tracking of monetary performance metrics such as net present value and return on investment through each scenario, are particularly interesting to commercial system stakeholders.

Monetary and non-monetary performance metrics can be concurrently illustrated in a lifecycle performance plot, as shown in Figure 8. Additionally, we are interested in evaluating the risk of defaults and the financial survivability of a design, which becomes visible the era level of the analysis. We may for example be willing to accept short periods of loss, in order to have higher overall probability of survival.

4.9. Step 9: Multi-era analysis

Multi-era analysis is a parallel process to the multi-epoch analysis. While multi-epoch analysis seeks to identify value-robust designs across the epoch space, the aim of multi-era analysis is to do the same in the era space. Considering the magnitude of the era space, it is computationally infeasible to find metrics parallel to those found in multi-epoch analysis. Smarter search mechanisms are needed to perform viable multi-era analyses, including methods for sampling epochs to eras, for example based on strategic system management decisions. The propagation of the era will be dependent on the trajectory of system decisions, especially when considering active value robustness and changeability. In addition, perturbations creating a shift from one epoch to the next will create path dependencies. For this reason, rolling horizon heuristics could be of interest in further research. A rolling horizon approach would not consider a fully rolled out scenario tree from the beginning, but continuously update the scenario tree as future uncertainties are resolved and decisions are made.

5. Discussion

5.1. On problem structuring

Design of engineering systems involves simplification of an initial ill-structured problem. There is a significant difference between the task of defining the ill-structured problem in terms of well-structured representations, and the task of solving a well-structured representation of the design problem. The Responsive Systems Comparison (RSC) method facilitates the problem definition processes, in addition to laying out a structured approach for solving the subsequent well-structured design problem. Taking relatively abstract business propositions into a more well-structured problem space represents in itself a design problem, as many alternative well-structured problems can be formulated. Thereafter, the well-structured problem can be solved, and resulting recommendations can be communicated to decision makers. Hence, this can be considered a two-stage abductive reasoning process, as illustrated in Figure 9.

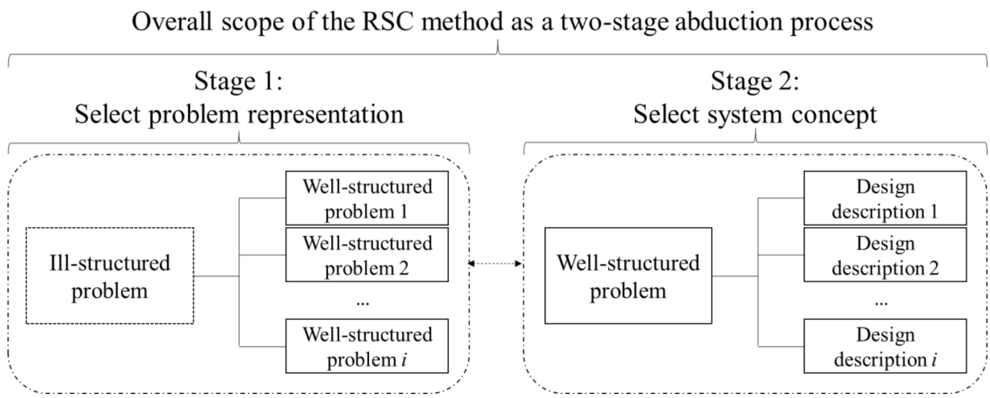

Figure 9: Making ill-structured problems well-structured, and solvable through two abductive stages.

Structuring an ill-structured problem represents in itself a result, as it reduces the ambiguities surrounding stakeholder preferences. For instance, the knowledge generated by explicitly relating a value proposition to the design space by producing a model, defines the design problem in such a way that it finally can be solved. The case study shows that the RSC method generates useful insights that will influence how design problems are framed, and thus how they are made solvable. Even incomplete RSC analyses provide value in early stage design problems, as they help structure the design process.

5.2. Profitability in a multi-attribute utility model

Evaluating commercial systems naturally require some attention given to monetary measures of value, beyond the trade-off between utility and cost. The model proposed in this case study incorporates profitability at the era-level, where non-dominated solutions are explored for a given contract with a fixed day rate. This enables identification of solutions that reduce costs for a given revenue, hence implicitly maximizing profitability. Two of the criteria of multi-attribute utility theory are violated when attempting to incorporate profitability as an epoch-level value attribute, namely non-redundancy and operationalization (Keeney and Raiffa 1993).

What generates value and what demands resources, or costs, should be kept separate according to the non-redundancy criteria. Since profitability already incorporates the costs, double counting becomes an issue when using profitability as an epoch-level value attribute. In the case of epochs with fixed revenue, attempting to use revenue alone as an epoch-level value attribute will not add differentiation among designs. However, use of an alternative well-structured problem representation, as illustrated in Stage 1 in Figure 9, may render revenue a meaningful epoch-level value attribute. Further, it is challenging to operationalize profitability as an epoch-level value attribute. One could argue that the perceived value of some profit depends on the size of the investment, rather than just the amount of money gained. A stakeholder would perhaps perceive the relative return on investment (ROI) as more important than the cash flows. However, issues with double counting again makes this approach troublesome. Additionally, running a loss is not easily modelled in a utility function, where contributions to utility are measured on a positive scale. A loss cannot be understood as adding positively to utility. Hence, a weakness when applying multi-attribute utility theory to commercial engineering systems design is that the profit cannot be rationally modelled within the framework.

In general, the value attributes selected depend on the location of system boundaries and level of abstraction, and not only on the stakeholder preferences. Inclusion of profitability at the era-level is found to be most meaningful for the case presented in this paper. This enables meaningful incorporation of short periods with negative profitability, with the aim of maximizing the overall profitability. Further, use of profitability as an era-level value attribute allows other interesting aspects of profitability to be considered, such as incorporation of constraints on losses and assessment of the effects of different stakeholder risk attitudes for the alternative designs.

6. Conclusion

In this paper, we show the applicability of the Responsive Systems Comparison method for structuring ill-structured design decision problems, making design problems more tangible. The strengths in the method with respect to the more well-structured design problem lie in the reduction of assumptions, supporting the decision-making process by communicating the trade-offs and compromises between multiple aspects of value. By applying the RSC method to a design case of an industrial offshore construction vessel, we show that commercial systems performance models can be integrated within the framework.

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Main Article 2

Overspecified vessel design solutions in multi-stakeholder design problems

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Abstract

Engineering design is characterized, in many cases, by the involvement of multiple stakeholders. The variety of stakeholders' expectations with regards to the output and outcome of a vessel design situation, and the differences in background, culture and information asymmetry among stakeholders, make it difficult to arrive at a common set of requirements and a mutually accepted vessel design solution. In this paper, we show how poor handling of expectations in multi-stakeholder arrangements may lead to overspecified design solutions and thereby, negatively affect business outcomes. We propose and test a set of metrics to measure the level of misalignment among stakeholders' expectations to identify and measure overspecification in vessel design alternatives. The measure can be used in tradeoff analysis against cost, in the decision process for selection among design alternatives. Hence, at equal cost, a higher degree expectation fulfillment may be preferred and selected. A case study is presented for the design of an offshore ship design based on a joint-venture ownership.

Keywords: multi-stakeholder, systems design, overspecification, ship design

1. Introduction

1.1. Background

Engineering systems like ships, real estate, and infrastructure projects have become larger and more complex and may involve larger quantities of resources and multi-field expertise (de Weck et al. 2011). Market globalization spurs companies to operate engineering systems in unknown environments, both geographically, culturally, and technically. Additionally, global sustainability goals increase the pressure for involving society and the environment in the development of new systems (Bocken et al. 2015). These factors have stimulated the integration of additional stakeholders in systems design, for example as businesses seek to form larger partnerships and collaborate. As the number of decision-makers involved in the design process grows, the total number of expectations, requirements, and constraints for the design increases. This will typically, increase the risk that a solution emerges that seeks to satisfy all individual expectations while being overspecified with respect to the expectations of each individual stakeholder. Hence, the final solution will give to each stakeholder more than what he or she originally asked for, leading to expensive solutions (Dwyer et al. 2014, Coman and Ronen 2010).

A definition of overspecification is given by Ronen and Pass (2008), who define it as the act of "defining product or service specifications beyond the actual needs of the customer or the market". Corresponding to this, they define overdesign as the process of designing and developing a product or service based on overspecification. In this paper, we will focus on overspecification arising from the existence of multiple decision-makers with partially misaligned expectations. We will, therefore, consider an overspecified solution a design solution that satisfies the expectations of all stakeholders, but at the same time over-satisfies the expectations of some of the individual stakeholders. Stakeholder expectations refers here to the needs, goals, and objectives of each stakeholder as communicated, in one way or another, to the designer and the remaining stakeholders involved in the design project (Hirshorn 2016). These expectations, that reflect the preferences of the stakeholders are then interpreted by the designer(s) who synthesize and define a set of functional requirements and constraints based on which a physical design is developed.

Multi-stakeholder design situations have been thoroughly studied in the engineering design literature, and numerous methods have been proposed to consolidate conflicting needs and preferences. Design methodology has been widely debated, with an editorial by Reich (2010) proposing two alternative worldviews; "praxis" and "scientism". The first worldview suggests that the design methods must be evaluated according to how well they work in practice, for example, by evaluating the performance of the final product. The second worldview suggests that design methods should maintain a theoretical rigor, for example by adhering to multi-attribute decision theory (Keeney and Raiffa 1993) or the axioms of social choice (Arrow 1950; Hazelrigg 1997, 1999). Some practical applications used to solve multi-stakeholder design situations have shown empirical success, although without addressing axiomatic implications. These applications include: quality function deployment, the analytical hierarchy process (Saaty 1990) and the Pugh controlled convergence method (Pugh 1990; Frey et al. 2009). Studies in mathematical psychology (Richards, McKay and Richards, 2002) and engineering design (Broniatowski, 2017) find that the implications of not meeting the social choice axioms are greatly reduced if decision-makers share similar knowledge structures or mental models of the selection problem.

While decision methods have had some success for some selection problems in design, the related problem of overspecification due to misaligned stakeholder expectations remains a challenge. Coman and Ronen (2010) provide an overview of several case studies from innovation, consumer goods and services, product development, and software engineering, and lists overspecification pathologies observed in these domains. Common pathologies include added system complexity and costs relating to unnecessary features, resulting in a divergence from objectives the product was launched to meet, and a difficulty of managing updates and latter design changes. The tendency to develop "one size fits all" solutions is one source of overspecification (Coman and Ronen 2010). This occurs when companies develop products to fit the requirements of multiple customer segments and therefore embed more functionality than what each customer strictly needs. Thompson et al. (2005) find through experiments on the human use of web-based products that the "one size fits all" approach leads to perceived overall product capability to increase while reducing actual product usability. Shmueli et al. (2015) find that overspecification in software development results from emotional attachment to features that are difficult to develop. These experimental results correspond well with theories in engineering design that argue that minimization of complexity maximizes the probability that functional requirements are met (Suh 1990; Braha and Bar-Yam 2007).

The maritime industry is another example of an industry where overspecified solutions commonly materialize. In the safety-focused offshore oil and gas industry, there are several examples of ships being overspecified to meet the expectations for several stakeholders in different market environments (Garcia, Brandt, and Brett 2016). Garcia et al. (2016) show that stakeholders like classification societies, charterers, and brokers, contributed to a growth in the total number of class notations for platform supply vessels. In good times, signified by high oil prices, this trend could be justified, as the costs of excessive requirements could be carried. In bad times, overspecification has caused an increase in the number of ships being taken out of service and put into lay-up, as the additional capabilities do not represent a premium on the charter rate of the vessels that would justify the added costs (Dahle and Kvalsvik 2016).

In this paper, we, therefore, investigate the relationships and effects of misalignment on stakeholders' expectations on overspecifying design solutions in design problems with multiple stakeholders and propose a set of metrics to identify and measure misalignment among stakeholder expectations. Our metrics could be used firstly to decide whether a given set of stakeholders should or not collaborate in design projects, depending on the symmetry of expectations, and secondly, to select a realistic set of requirements given the expectations of the different stakeholders and the context at hand. With respect to the Reich's (2010) dichotomy of decision methods, the proposed metrics are positioned to impact design practice, particularly in ship design. To demonstrate the use and applicability of the proposed metrics, a simplified version of an industrial case study from the design of a large offshore construction vessel ordered by a joint-venture of two ship owners is presented. Offshore construction vessels perform a variety of tasks in oil and gas field development including inspection, maintenance and repair, lifting and construction of subsea structures, and increasingly contribute to the installation of offshore wind farms.

We limit the scope of this paper to cover problems of collaboration and negotiation among key decision-makers during early-stage design, specifically in the phases of task clarification and conceptual design (Pahl et al. 2007). This corresponds to the phases of the design process in which most costs are settled (Mistree et al. 1990; Erikstad 2007). Hence, we will not consider the complexities of collaboration within design teams (see e.g. Braha and Bar-Yam (2007), Grogan and de Weck (2016) or Eisenbart et al. (2017) for empirical results), even though we acknowledge that preferential differences among members of the designing organization also play a role in later design phases.

1.2. Literature review

Design processes which involve multiple stakeholders can lead to overspecified solutions, as it is generally difficult for stakeholders to find mutual amicable agreement on the expectations of the design, both, on output and outcome. A reason for this can be found in the diversity of disciplines and perspectives among stakeholders. For example, in ship design, stakeholders who influence design include the ship designer and ship builder, vessel operator, end customer and ship owner or investor, among others. Each of these informs the design from technical, operational and commercial perspectives. This misalignment among stakeholders' expectations is intensified when stakeholders have fuzzy mental images of what they need or of what is being designed (Richards et al. 2002; Rexfelt et al. 2011; Broniatowski 2017). Misaligned expectations result in an excessive addition of features, as a design process characterized by difficult collaboration and negotiation unfolds. In this section, we review the literature on overspecification and multi-stakeholder decision-making, before we position the current work within the debate regarding multi-stakeholder decision-making in engineering design, and finally discuss the role of collaboration and negotiation in engineering design.

The concepts of overspecification and overdesign are outlined by Ronen and Pass (2008). They consider these concepts to encompass specification and design going beyond what is required according to stakeholder needs. Coman and Ronen (2010) comment that this is a rather broad definition, that can include both the act of setting too narrow tolerances, as well as adding unnecessary features. They present a series of illustrative case studies from several domains and identify corresponding sources of overspecification and resulting pathologies. Pathologies resulting from overspecification include excessive costs and delayed product deployment. Common sources of overspecification range from the inclusion of functionality to assure compliance with future needs, the addition of functionality for marketing purposes, to the inclusion of functionality to meet the needs of customers with different needs. A more recent review (Shmueli and Ronen 2017) finds a large gap in the literature on overspecification. Walker (2013) identifies three major problems associated with overspecified design; 1) backfire – the additional requirement would have an opposite or undesirable effect to what initially intended, 2) added costs, and 3) ruined individual stakeholders' expectations. In some cases, design for excess capabilities is intentional and used as a strategy for adapting to new, changing or uncertain needs (Allen et al. 2017), similar to safety margins added for the expected design performances (Eckert and Isaksson 2017).

There have been several experimental studies that investigate sources of overspecification (Thompson et al. 2005; Shmueli et al. 2015). Shmueli, et al. (2015) find experimentally that software developers become emotionally attached to features that they specify. Their results show that features are perceived by developers to be more valuable if they are difficult and time-consuming to develop. Thompson et al. (2005) find that an overdesigned product increases initial sales, as the perceived capability level for the product is higher. Before buying a product, the users tend to weight capability higher than usability. However, the excessive number of features comes at the expense of usability. As a result, relatively few customers will end up using the product in the longer term, resulting in a decrease in long-term sales.

The results resonate with central design theories that see an inherent trade-off between the number of functional requirements, and the probability of meeting functional requirements (Suh, 1990; Braha and Maimon, 1998). Additionally, there is correspondence between the experimental results of Shmueli, et al. (2015) and Thompson et al. (2005), and findings from the maritime industry, where multi-functional ships have mostly fallen out of fashion, as they are difficult to operate profitably (Stopford 2009), apart from in the oil and gas industry (Ulstein and Brett, 2015). In that domain, Garcia et al. (2016) explain, based on analyses of the offshore vessel fleet, how good markets lead to “more is always better” strategies in ship design that favor increased functionality over reduced cost, with detrimental consequences for the industry when the market state turn sour. Further, recent studies on the offshore vessel service market show that additional capability do not necessarily have major consequences on vessel earnings, while it may increase the likelihood of the vessel to win a contract (Dahle and Kvalsvik 2016; Tvedte and Sterud 2016). The additional costs associated with additional capabilities may decrease the overall profitability of the vessel, especially in bad market conditions.

Many overspecified designs are the result of the aggregation of requirements in multi-stakeholder problems where the stakeholders have misaligned expectations. Ross et al. (2010) refer to design processes in which conflicting expectations are resolved by aggregation of requirements as “easy compromises”, and refer to the outcomes as “gold-plated” designs. These are solutions that satisfy the expectations of all stakeholders and consequently over-satisfy the expectations of individual stakeholders, as these expectations typically are not 100% aligned, which suggests that the expectations of some stakeholders ae inconsistent with their mental models. The aggregation of expectations has been explored in more detail by Dwyer et al. (2014), who distinguish among three potential levels of aggregation: requirements aggregation, mission aggregation, and parameter aggregation, and additionally the disaggregation among organizational components. They assess the economic effects of projects involving multiple stakeholders, and find that such projects are typically costlier, referring to this phenomenon as “the cost impacts of jointness”. Alignment of stakeholder expectations in a common set of requirements and constraints is hence central to success and economic performance. Divergence among stakeholders regarding the interpretation of problems and solutions influence their behavior in interactions, their strategic choices and their selection of solutions (Endsley 1995; Corsaro and Snehota 2011). Stephen and Coote (2007) suggest that the alignment of objectives (here expectations) in multi-stakeholder problems depends on relational behavior. Such relational behavior should be built on a culture of maximization of joint utility over individuals’ self-interest. Alignment still can become challenging when stakeholders have additional expectations beyond pure problem solving, such as non-economic satisfaction and disagree about what strategy will lead to maximization of profits in the long term. Such discrepancies also easily occur, when stakeholders are not really aware of the cost implications of such expectations (Brett et al. 2018). This could be partially resolved by incentivizing open communication among stakeholders (Franssen and Bucciarelli 2005), resulting in shared expectations (Ayers 2015).

The positive effect that expectation alignment (needs, goals, objectives) has in process and organizational performance is not unknown in management literature (Ayers 2015; Fitzpatrick et al. 2015). Fitzpatrick et al. (2015) describe alignment as the degree to which expectations are in agreement and serve in conjunction with one another. One of the critical factors to expectation alignment in multi-stakeholder problems is the knowledge of how each individual affects the expectations of the group. Hence, if stakeholders are aware of the group’s expectations and their contribution to the expectations, they will contribute more positively to group expectations (Ayers 2015).

The difficulties surrounding multi-stakeholder design problems have been widely studied in the engineering design context and has been subjected to much debate. Reich (2010) summarizes the conflict by outlining two alternative worldviews, "praxis" and "scientism": The "praxis" perspective judges decision-making methods according to the actual improvement of design practices and is supported by the proponents of methods like quality function deployment, analytical hierarchy process (Saaty, 1990), and Pugh controlled convergence (Pugh 1990; Frey et al. 2009). The "scientism" perspective suggests that design decisions should be derived by application of methods that builds on rigorous theory from other decision-making domains, exemplified by the multi-attribute utility (Keeney and Raiffa 1993) or social choice theory (Arrow, 1950).

To the proponents of the "scientism" worldview, a central issue for the application of design methodology to multi-stakeholder design problems is how these design situations are affected by Arrow's Impossibility Theorem (AIT) (Arrow, 1950). If stakeholders' preferences differ among members in a group, it is impossible to guarantee an optimal decision for the group, considering that each rational stakeholders will want to make decisions maximizing their own utility (Hazelrigg 1996, 1997). AIT proves this mathematically and shows that even in groups consisting of rational stakeholders only, irrational, cyclic preferences are plausible. To comply with the axioms of social choice, design decisions may, therefore, require a dictator, where only the preferences of one stakeholder are considered (Hazelrigg 1996, 1997, 1998, 1999). The applicability of AIT to group decisions in engineering design has been questioned by several authors (Scott and Antonsson 2000; Keeney 2009) and elaborated on for multi-objective problems by yet others (Franssen 2005). A game-theoretic extension (Franssen and Bucciarelli 2005) consolidated the risk of cyclic preferences on the group level (as suggested by Hazelrigg), with the need for two rational decision-makers to find an optimal solution in a collaborative situation. At its center, the debate over the application of AIT boils down to a question of whether there exists sufficient commonality among stakeholders to avoid cyclical preferences and selecting a stable, desirable design solution. In fact, simulation results show that there is a low probability that cyclical preferences impact the selection, once similarities in mental models are assumed. Richards et al. (2002) and Broniatowski (2017) take an intermediate position and suggest that if stakeholders share a mental model or knowledge structure of the problem situation, the probability of arriving at irrational outcomes is dramatically reduced. With minimal structure the probability of irrational outcomes is found to be below 5%, dropping below 3% with slightly stronger limitations (Broniatowski 2017). Similarly, Richards et al. (2002) find that about 96% of the multi-stakeholder problems can arrive at rational outcomes if stakeholders share mental models. Even under the assumption that these stakeholders may have a common mental model (considering that they work in the same industry (Endsley 1995), and understand the objectives of the multi-stakeholder collaboration (Klimoski and Mohammed 1994)), their preferences may differ, and so their expectations. With respect to our ship design case, it is reasonable to question the degree to which two ship owners from different countries, with corresponding differences in culture and legal environment and with two clearly different business strategies will share preferences with regards to the selection of a vessel design.

Independent from the discussions about the implications of AIT on engineering design, other researchers propose to develop a common understanding of the problem at hand, in cases where expectations may be misaligned. Kusiak and Wang (1994) present a framework for negotiation in design that derives a compromise solution by iteratively attempting to maximize the utility of individual stakeholders, while concurrently ensuring that all individual stakeholder expectations are met. Phillips and Costa (2007) suggest combining multi-criteria decision analysis (MCDA) with decision conferencing to build a shared understanding of the problem and find a common way forward. Similarly, Gray (2004) recommends identifying differences in stakeholder frames of reference with regard to the problem, as a basis for developing a new common frame, and support a collaborative solution. A similar approach is presented by Fitzgerald and Ross (2014), who suggest that the resistance to compromise among stakeholders is typically a cause of initial unrealistic frames, suggesting rather starting from a common frame reflecting the gains from mutual value. Likewise, Topcu and Mesmer (2017) suggest that initializing design negotiation with given stakeholder requirements implies that design starts from a reduced design space, compared to the space of all technically feasible solutions. As a remedy, they propose that design with multiple stakeholders should commence from a common basis of values. These arguments can be supported by the reasoning underlying value-focused thinking (Keeney 1992); when starting from common values, a general basis on which stakeholders can agree served as the starting point for design. Keeney (2009) argues that the misalignment among stakeholder's expectations could be partially abolished by productive discussions. He also argues that such discussions cannot take place if information, knowledge, and judgments are not made explicit. Flow and Payne (2011) suggest the facilitation of dialogue and knowledge sharing among stakeholders as a way to identify value co-creation opportunities and avoid the results of poor discussions. This dialogue should result in a common understanding of the problem at hand, the sharing of preferences or the identification of less essential expectations.

Having studied the literature on overspecification due to the existence of multiple stakeholders in engineering design problems and understanding the positive effect that expectation alignment has on the performance of the group, we see a need for measuring the degree to which stakeholder expectations are misaligned. We also recognize the need for metrics and graphical representations which could support the exchange of information among stakeholders and recognize the inconsistency between their preferences and mental models. Currently, the concept of misalignment is not well-defined and lack a generally accepted approach to measurement (Corsaro and Snehota 2011). The metrics we propose are intended to contribute to an improvement of design practice and can be applied to multi-stakeholder design problems, independently of conclusions made in the debate about Arrow's Impossibility Theorem.

2. Overspecified solutions: a result of multiple stakeholders

2.1. What is a multi-stakeholder overspecified solution?

A multi-stakeholder overspecified design solution is a design that satisfies the expectations of all relevant stakeholders, and typically, over-satisfies the expectations of individual stakeholders, as those expectations are not 100% aligned. Hence, multi-stakeholder overspecification is the result of the aggregation of misaligned expectations in multi-stakeholder design problems. It is, typically, a consequence of a lack of relevant information, poor negotiation, or ineffective collaboration among stakeholders, resulting in inconsistent preferences.

Our case study is a joint-venture of two ship owners who have decided to build a large offshore construction vessel is in focus. Owner 1 is interested in a large, generic construction vessel to operate in the Gulf of Mexico (GoM). On the other hand, Owner 2 is interested in a specialized vessel to operate mostly in the North Sea. There will be some commonalities, for example having a crane, or a propulsion plant, although not necessarily of equal capacity, and some additional expectations from both sides, such as a larger accommodation capacity to operate in the GoM or a larger propulsion plant to operate in the North Sea. See Figure 1.

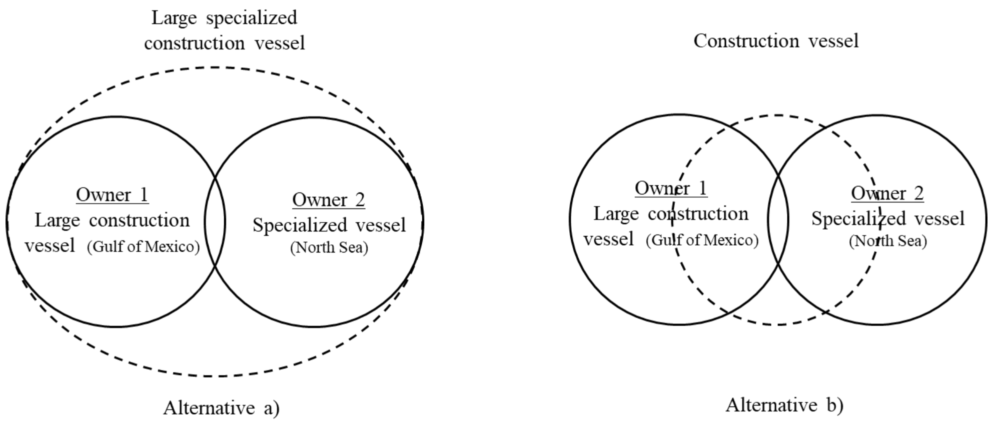

Figure 1. Ship design case with two stakeholders.

As a consequence of the misaligned, not agreed upon expectations, the final design solution may result in a large specialized construction vessel, Alternative a) Figure 1. Such a large construction vessel will fulfill the expectations of both stakeholders but may perform sub-optimally for each of the two stakeholders. The propulsion plant may be unnecessary large when operating in the GoM, where the probability of wave heights above 3,0 m Hs is below 2%, compared to a 35% probability in the North Sea, and the vessel will have an excessive accommodation for the demands of the North Sea. As consequence, Owner 1 will have a vessel which represents an initial higher investment and with higher fuel consumption (larger propulsion plant), which will make it less competitive than peer vessel purposely designed for the Gulf of Mexico. Similarly, Owner 2 will have a much larger accommodation that competing vessels, that may represent a disadvantage. Alternatively, the design solution may result in an intermediate alternative. Alternative b), Figure 1. This design solution may result in a medium sized vessel designed to operate in both regions, although with the limitation of operating in the North Sea only up to a certain sea state limit. The given limitations should not compromise the capability of the vessel to gain contracts in that region. As a result, the propulsion plant will not be overspecified to the same degree when operating in the GoM, nor the accommodation when operating in the North Sea. With this compromised solution (Alternative b)), the overall performance of the design alternative may be higher than the overspecified design (Alternative a)).

2.2. Alignment and misalignment of expectations

The terms of alignment and misalignment are intuitively appealing, but they lack a clear analytical definition (Corsaro and Snehota 2011). The misalignment of design expectations can be measured by two aspects, one relating to the factor itself (functionality, capability) and the second relating to the scale of the factor (capacity). The two owners from our previous example may be aligned regarding the factor crane, but the scale, maximum lifting capacity, may be different. Hence, they will be aligned in terms of a factor but still, misaligned in the scale. We argue that the approach to follow in design with regards to a multi-stakeholder problem will depend on the level and type of misalignment among the stakeholders. In Figure 2 we present the four potential cases of alignment and misalignment of expectations for a two-stakeholder problem. To simplify, we consider here only factor misalignment, and leave to the side, initially, scale misalignment.

Case a) represents the situation where both stakeholders have the same expectations, eg. two ship owners who want to operate a construction vessel in the Gulf of Mexico. Case b) represents a situation with partial alignment, where stakeholder A and B have some common, aligned expectations and additionally, each of them has some individual expectations. Eg. two shipowners who want to operate a construction vessel, one of them in the Gulf of Mexico and the other in the North Sea. A partial alignment is also Case c). In this situation, one of the stakeholders has expectations that are surpassed by those of the other stakeholder. In our earlier example, the second stakeholder, would operate the vessel in both, the Gulf of Mexico and the North Sea. Finally, a full misalignment of expectations is presented in Case d), where the stakeholders do not share any expectations. Eg. one shipowner who needs a construction vessel for the Gulf of Mexico and another shipowner who needs a container vessel for operation in the Mediterranean.

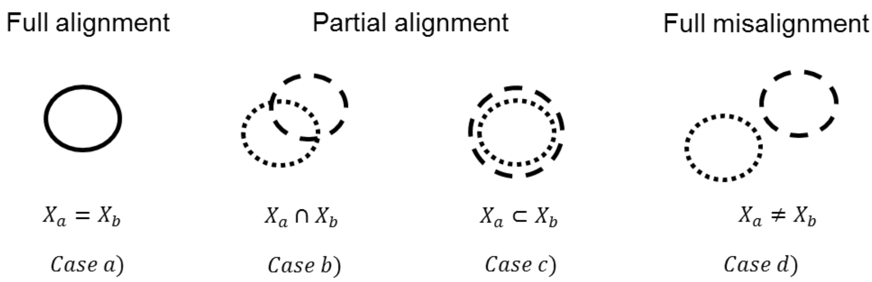

Figure 2. Alignment and misalignment of expectations.

The consequences of a misalignment of expectations in the performance of the final design will depend on the degree and type of misalignment. As such, an overspecified design resulting from a partial alignment X_a∩X_b may present poorer performance than the one resulting from a partial alignment of the type X_a⊂X_b, Figure 2. In the first case, the design consists of a set of common requirements plus two sets of additional expectations from the two single stakeholders. A $X_a \subset X_b$ misalignment represents only additional expectations from one of the stakeholders, therefore reducing potential negative effects on performance.

Building on our example of two shipowners presented earlier in this article, we can identify the strategy of Owner 1 as “being a leading supplier of subsea construction services in the Gulf of Mexico”, while Owner 2 pursues “being worldwide leader on well intervention services”. The two strategies present a partial misalignment, in line with the Case b) reflected in Figure 2. Both stakeholder’s strategies are aligned in performing well intervention operations in the GoM, while Owner 1 has additional expectations with regards to performing inspection, maintenance and repair (IMR) and the installation of subsea umbilicals, risers and flowlines (SURF) in the GoM, and Owner 2 with regards to performing well intervention operations in alternative regions such as Asia, North Sea or Africa (Figure 3). Hence, although both stakeholders hare a common understanding of the offshore oil & gas market, their preferences will defer as result of their different strategies. These discrepancies and misalignment on the strategies of the two shipowners are the drivers of the misalignments on their expectations, therefore incentives of a final overspecified vessel design.

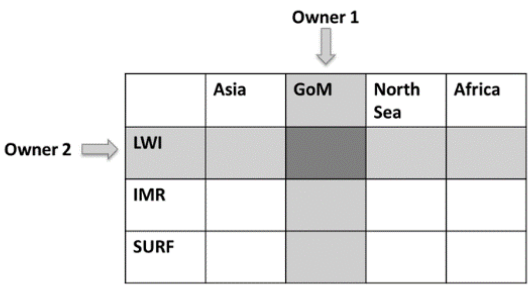

Figure 3. Misalignment on stakeholder strategies for the design of a construction vessel.

2.3. Measuring alignment and misalignment of expectations

Now that the concept of multi-stakeholder overspecification has been introduced, we propose a set of metrics for quantifying the alignment and/or misalignment among stakeholders’ expectations. This measure could be used as a support during the negotiation process, and as a basis for the development of a common set of requirements and constraints. As a starting point, and to get a better perception of the misalignment among all the stakeholders, we recommend the use of graphical representations in the form of spider plots for representation of individual expectations and as bases to build a common understanding of the problem at hand among the stakeholders. The use of this type of representation may be limited to only a few stakeholders, although it should be representative of most practical design problems. Here, a compromise should be made between a number of stakeholders and the perceptual complexity they bring into decision making.

Furthermore, we propose a two-factor measure to quantify the alignment of stakeholder’s expectations, which pairwise compares the expectations of each individual stakeholder with the equivalent expectations of the other stakeholder. The first factor measures the alignment of expectations, while the second gives an indication of the additional expectations from the other stakeholder. Hence, we first identify how well the expectations of both stakeholders match, and then represent the amount of effort - additional expectations - a stakeholder should be willing to accept in order to fulfill the expectations of the other stakeholder. Both factors are presented in relative terms with respect to the number of expectations of the individual stakeholder. Finally, the degree of misalignment (DoM) is calculated as presented in Equation (2), combining both factors.

$$Alignment_{A,B} = \left(\frac{No.\ of\ aligned\ expectations}{No.\ of\ expectations\ stakeholder\ A}\ \&\ \frac{No.\ of\ additional\ expectations\ from\ B}{No.\ of\ expectations\ stakeholder\ A}\right) \quad \textit{Equation 1}$$

$$\mathrm{DoM}_{\mathrm{A,B}} = \left(\left(1 - \frac{\mathrm{No.\ of\ aligned\ expectations}}{\mathrm{No.\ of\ expectations\ stakeholder\ A}}\right) + \frac{\mathrm{No.\ of\ additional\ expectations\ from\ B}}{\mathrm{No.\ of\ expectations\ stakeholder\ A}}\right) \quad \textit{Equation 2}$$

The DoM measure gives an indication of how close the expectations of a pair of stakeholders are. A DoM of 0% represents the full alignment of expectations, and above that, the misalignment increases. Further, the two-factor measure proposed gives a better understanding of the type of misalignment between the pair of stakeholders. Considering the two-stakeholder problem of Figure 2, an AlignmentA,B of 100%, 0% would represent a pair of stakeholders with full alignment of expectations, Case a), and an AlignmentA,B of 40%, 30% would represent a partial alignment, where only 40% of the expectations of A are aligned with those of B, and B has a 30% additional expectations, Case b).

Further, a measure is proposed to identify how "well" a design alternative fulfills initial stakeholder expectations. On an individual stakeholder basis, we measure the individual expectations fulfillment index (IEFI). The IEFI represents the level of fulfillment of the individual stakeholder's expectations. Values below 100% represent designs which do not fulfill all the expectations of that specific stakeholder, while values above 100% represent designs beyond stakeholder's expectations. In this case, we consider both factor and scale of the expectations. The IEFI is given in Equation (3).

$$IEFI_i = \frac{No.of\ expectations\ met_i}{No.of\ expectations_i}\ , i = stakeholder,\ scale\ [0 - 100\%] \quad \textit{Equation 3}$$

These set of metrics imply that stakeholders' expectations are described numerically, or that they can be converted to numerical quasi-metric form by Likert scales (1 to 7, e.g.) or as binary terms. Some practical examples are ice strengthening (1 if included, 0 if not); or luxury level in cruise vessels (1 to 5), equivalent to the Stars of hotels.

3. Methodology

The purpose of the metrics here proposed is to support the design of better engineering systems in multi-stakeholder design problems by facilitation the building of a common set of preferences among the different stakeholders. The implementation of these metrics relates to the initial phases of the design process, which are generally described as stakeholder identification, requirement elicitation and generation of design alternatives (Walden et al. 2015). In Figure 4, we present a model of a generic design process to highlight the role and applicability of the metrics proposed in this article.

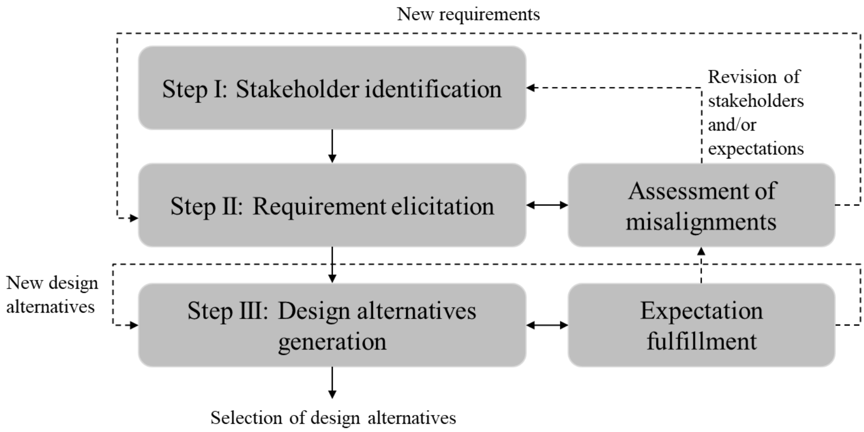

Figure 4. A simplified model of a design process.

As a starting point, the identification of stakeholders will bring us information regarding who is involved, who can affect and who is affected during the decision-making process (Fülöp 2005). This step should clarify who are the stakeholders to be considered in the following processes, as well as give information regarding their contributions. Although many stakeholders may affect or are affected by the process, the designer should select only the most relevant. A lower number of stakeholders will improve traceability (Cameron et al. 2008).

Each of the stakeholders involved in the design process will have a set of expectations with regards to the design project, which are typically communicated to the designer on a written document. It is the responsibility of the designer, to homogenize their expectations in a common set of requirements. The set of requirements defined by the designer, together with the constraints of the project, will define the final the design space. The design space may be too narrow or non-existent if the expectations of the different stakeholders are misaligned. At this stage, the designer may evaluate the misalignment of stakeholder expectations and communicate with them the effect of some of their expectations in the requirements and constraints of the project and consequently on the design space. As result, the number of stakeholders participating in the project and their expectations may be revised, leading to a new set of requirements, constraints and consequently, design space.

Finally, the designer will select a limited number of design alternatives among all the possible within the design space. These alternatives could be evaluated in terms of how well they fulfill the expectations of the different stakeholders. This evaluation may lead to the definition of new design alternatives.

In our case study, the metrics are implemented as a support tool of the Ulstein's Accelerated Business Development (ABD) process (Brett et al. 2006; Ulstein and Brett 2012). The Ulstein ABD is used today by Ulstein in structuring the conceptual ship design process. It provides guidance and decision-making support to the stakeholders involved in the decision-making process (Brett et al., 2006), especially in those cases characterized as wicked or ill-structured problems. To reduce the ambiguity of stakeholder expectations, within the ABD process, all the stakeholders are invited to a common workshop, where their expectations are contrasted with each other, and a common set of requirements and constraints is elicited. During the workshop, the different stakeholders can explore the consequences of their expectations in the final vessel design and its performance. The metrics presented and used in this approach are tool to facilitate the communication among stakeholders and the designers, finding a common, and mutually agreed upon set of requirements and constraints that satisfy all the stakeholders; and finally select a vessel design solution.

4. Multi-stakeholder ship design case

4.1. Collaboration in ship design

Collaboration within the maritime industry has become popular, as it has been recognized as a flexible, affordable, and safe strategy for innovation in the pursuit of competitive advantage (Das and Teng 2000), incentivizing the creation of joint-ventures, synergies, and partnerships, among others. Examples of recent collaboration are the alliances for container liners. Although created with the purpose of reducing cost and risk, Fusillo (2006) highlights that such alliances may limit the capability of liners to differentiate themselves, and consequently strengthening the emphasis on price. Another example of multi-stakeholder collaboration is the “DSVi collective” initiative (Subsea 7 2016), where six operators benefit from continuous access to a diving support vessel through a collaborative agreement. The loss of flexibility with respect to time available, due to the vessel performing operations for another of the operators when needed, is compensated for by the lower overall operational cost. Agreements are also present in the design and construction phases. Example of this include the arrangements between Fincantieri and CSSC to design and build cruise vessels for the Chinese market (Yu 2016) and Ulstein and SeaOwls to develop the next generation self-propelled heavy-lift jack-up vessel (Ship&Offshore 2017).

Multi-stakeholder projects in the maritime industry are formed, in most of the cases, to overcome challenges such as geographical location, expertise, culture, and language, or to cope with the challenges caused by business cycles and volatility of the market (Solesvik 2011). In many cases, these collaborative strategies do not have outcomes as initially intended, resulting in the likely closure of the project, the bankruptcy of the company or the dissolution of the cooperation.

4.2. Problem description

In this paper, the decision-making process for an investment in a new large offshore construction vessel (OCV), as presented by Pettersen et al. (2018), is assessed. Both design, construction, and operational phases are considered as influencing the conceptual design phase, so stakeholders involved in those phases should be considered. The distinctiveness of this case study is the role of a joint-venture ownership, two shipping companies joining resources to capitalize on a business idea on the intersection of their individual value propositions, see Figure 3.

Offshore construction vessels are vessels involved in the installation, repair, maintenance, and decommissioning activities of offshore oil & gas projects, among others. There are a variety of different maritime operations related to the offshore construction sector, from the installation of big subsea structures to diving support or inspection activities. Each of these activities requires basic characteristics intrinsic in the design, such as personnel on board (POB), deadweight (DWT), cranes, light well intervention tower (LWI) or dynamic positioning (DP) capabilities.

4.3. Analysis

This paper is neither going through the entire process of identifying stakeholders, defining their expectations, the consequent definition of requirements, and constraints, nor the definition of the design space and corresponding design alternatives. Those steps were carried out in detail by Pettersen et al. (2018). We use their findings to further explore the role and effect of multi-stakeholders and misalignment of stakeholders' expectations in design.

The definition of functional requirements based on stakeholder expectations is often the first step in the design process (Suh 1990). In practical cases in the maritime industry, stakeholders define their design expectations and preferences by a single reference number, equivalent to design criteria, which is communicated to the designer. The main dimensions of the vessel, length, breadth, the speed or the cargo carrying capacity. In most cases, these expectations are open for discussion and include acceptable deviations that, although not articulated, should be considered by the designer when defining the design requirements and constraints that will be used further in the design process. Table 1 includes a numerical representation of the expectations towards the vessel's newbuilding project. The list defines the expectations in the form of target values for capacities and capabilities as communicated by the four stakeholders. This list is not exhaustive, but it includes the most relevant stakeholders, those with more power in this specific project. In this case, we have considered the two ship-owners forming the joint-venture ownership, an Oil & Gas company, representing the end-user, and the shipyard which will build the vessel. A quick analysis of Table 1 depicts some alignments and misalignments regarding the expectations of the four stakeholders.

Table 1. Initial expectations of different stakeholders towards the vessel's new building project.

Vessel functions	*Expectations*	*Stakeholder 1*	*Stakeholder 2*	*Stakeholder 3*	*Stakeholder 4*
Accommodate people	POB (people)	200	150	100	350
Carry cargo	DWT (tonnes)	10,000	7,000	12,000	6,000
Lifting cargo	Crane (tonnes)	400	200	-	50
Maintain subsea wells	LWI (tonnes)	-	300	600	-
Machinery redundancy	DP Class (#)	2	3	3	2
Sea state operability	Region (H_s) (m)	1,0	3,0	1,0	2,0

Stakeholder 2 is the one with the highest number of expectations, six compared to the five of the other three stakeholders; although its expectations are lower in terms of scale. Stakeholder 1, 3 and 4 seem to look for specialized a vessel (Stakeholder 1 is focused on crane and lifting capacity, Stakeholder 3 on well intervention capabilities and Stakeholder 4 on accommodation capacity). Stakeholder 2, however, has a broader list of expectations. Figure 5 provides a graphical overview of the stakeholder expectations. A deeper analysis of Figure 5, gives the impression that only for the DP Class, two stakeholders require the highest scale, for all the other expectations, the largest scale expectations almost double the expectations from the rest of stakeholders. In Figure 5 we have normalized the values, so the highest value of each scale is represented as 1,0.

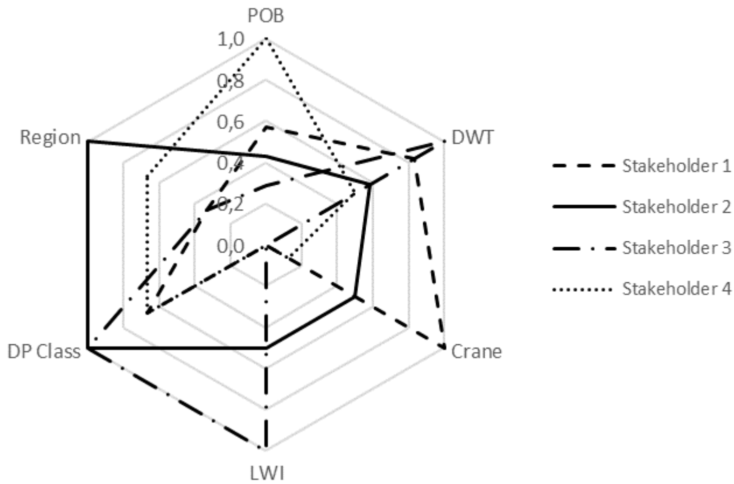

Figure 5. Graphical representation of normalized expectations from the individual stakeholders.

As a result of the generation of design alternatives, we consider four potential vessel concept design alternatives, presented in Table 2. Although the original design space includes more than just these four design alternatives, we have chosen this number of four for simplicity of representation. Design 1 represents the gold-plated design covering the expectations of all the stakeholders. Designs 2, 3 and 4 are three alternative design solutions fulfilling partially the initial expectations of the stakeholders.

Table 2. Four vessel design alternatives.

Vessel design specifications	*Design 1*	*Design 2*	*Design 3*	*Design 4*
POB (people)	350	50	150	250
DWT (tonnes)	12 000	8 000	10 000	6 000
Crane (tonnes)	400	200	-	200
LWI (tonnes)	600	-	300	-
DP class (#)	3	3	2	3
Region (H_s) (m)	3	1	2	2
Estimated newbuilding price ($ mill)	200	75	120	100

4.4. Results

Our analysis builds on the same case study material as Pettersen et al. (2018). Here we start by identifying the misalignment of expectations among stakeholders. Table 3 includes the pairwise comparison of stakeholders' expectations in terms of alignment and additional expectations.

Table 3. Pairwise AlignmentA,B - metric of expectations among the four stakeholders.

	Stakeholder 1	Stakeholder 2	Stakeholder 3	Stakeholder 4
Stakeholder 1	100 % & 0 %	80 % & 0 %	80 % & 20 %	100 % & 0 %
Stakeholder 2	100 % & 20 %	100 % & 0 %	100 % & 20 %	100 % & 20 %
Stakeholder 3	80 % & 20 %	83 % & 0 %	100 % & 0 %	80 % & 20 %
Stakeholder 4	100 % & 0 %	80 % & 0 %	80 % & 20 %	100 % & 0 %

A first evaluation of the results in Table 3, shows that Stakeholder 2 has 20% additional expectations than the other three stakeholders, although, at the same time, it is aligned with all their expectations (100% , 20%). Stakeholder 3, on the other hand, is only aligned with 80% and 83% of the expectations of other stakeholders and requires 20% additional expectations compared to Stakeholder 1 and 4. When calculating the DoM, as presented in Table 4, we can see that Stakeholder 3 presents a higher degree of misalignment than Stakeholder 2. Looking at the overall alignment of each stakeholder with the group, it is clear that Stakeholder 3 has the highest degree of misalignment.

Table 4. The degree of misalignment (DoM) between the four stakeholders.

	Stakeholder 1	Stakeholder 2	Stakeholder 3	Stakeholder 4	Group
Stakeholder 1	0 %	20 %	40 %	0 %	60 %
Stakeholder 2	20 %	0 %	20 %	20 %	60 %
Stakeholder 3	40 %	17 %	0 %	40 %	97 %
Stakeholder 4	0 %	20 %	40 %	0 %	60 %

A potential interpretation of the results is that Stakeholder 3, as the one with the highest degree of misalignment, presents a large inconsistency between his expectations and the common mental model. This stakeholder is looking for a specialized vessel for well intervention operations, while the other stakeholders are interested in a more generic offshore construction vessel, and their expectations do not really match.

Similarly, the individual expectations fulfillment index (IEFI) assesses the fulfillment of expectations for each design alternative. Table 5 presents the IEFI of four design alternatives for the four stakeholders under consideration. The results show how the gold-plated design fulfills all the initial expectations of all the stakeholders, while the remaining designs under fulfill some of them.

Table 5. Individual expectation fulfillment index (IEFI) of four design alternatives.

	Design 1	Design 2	Design 3	Design 4
$IEFI_1$	100 %	60 %	80 %	80 %
$IEFI_2$	100 %	67 %	67 %	67 %
$IEFI_3$	100 %	60 %	40 %	80 %
$IEFI_4$	100 %	80 %	80 %	100 %

Experience from our vessel design activity suggests us that a traditional ship design approach would most likely select Design 1, the one fulfilling all the initial expectations of the individual stakeholders, as the most promising final design solution, although this design would be also discarded with relation to their associated newbuilding costs. Design 2, Design 3, and Design

4 would typically, be discarded as they are not fulfilling all the initial expectations. The resulting reduced design space may discriminate against design solutions with higher potential overall value. One initial observation from Table 5, is that Stakeholder 2 and Stakeholder 3 are the ones with stricter expectations and the lowest IEFI, therefore they are the largest contributors to the overspecification. Small relaxation of their expectations may lead to Design 2, 3 or 4 becoming good enough. As an example, a relaxation of expectations for Stakeholder 2 would make Design 4 a good enough design alternative, fulfilling 80% or more of the expectations, while representing a cost reduction of 100 mill USD.

4.5. Interpretation of results

This case study represents a typical ship design situation. It includes four stakeholders with different expectations, three of them looking for a specialized vessel, and a fourth stakeholder looking for a more generic vessel design. The results show that the aggregation of stakeholders' expectations in a common set of requirements would lead to the selection of a multi-stakeholder overspecified design. This design is shown to outperform the rest of the designs in terms of specification, but it has a cost penalty that may reduce the value perceived by the single stakeholders. Similarly, the overspecification may be perceived negatively by the single stakeholders. As an example, for Stakeholders 2 and 4, having a 400 tonnes crane rather than 200 tonnes as expected may be perceived negatively, as it may reduce the speed and precision of the operations, requires more maintenance work and increases the initial investment.

The consequences of the misalignment among stakeholders' expectations are reflected in Figure 6. The graph compares the initial expectations of Stakeholder 1 with the four design solutions presented in Table 2. A first impression shows the multi-stakeholder overspecification of Design 1, with scores above 1,0 in almost all the expectations. Design 1 is overspecified in all the expectations except for the crane, where it fulfills exactly Stakeholder 1 expectations. Similarly, it shows how some of the other designs have a better fit to the initial expectations of Stakeholder 1, such as Design 2, although they may require some relaxation of expectations.

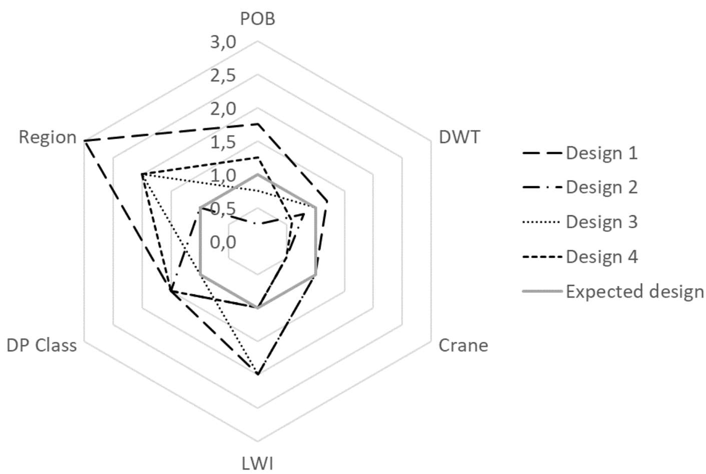

Figure 6. Representation of four design alternatives regarding the fulfillment of Stakeholder 1 expectations

Misalignment of expectations may be reduced when the different stakeholders recognize that their preferences are inconsistent with their common mental model. Hence, we propose here the facilitation of productive discussions as the way forward in multi-stakeholder problems, following the practices within Ulstein accelerated business development (ABD). Stakeholders may find a common understanding of the problem reducing, therefore, the overspecification of the final design solution and increasing the effectiveness of the vessel design process. Sensitivity analysis and graphical representations such as the ones proposed should support these productive discussions, and lead to better, quantitative decisions. Poor negotiation in ship design problems has already led to long, ineffective designs processes. In many cases, a final best design solution is never found, as the stakeholders cannot agree on what is better for them, or on how much pay for it. In other cases, a final best design solution is found, yet, stakeholders may suffer the negative effects of the overspecification of the vessel, represented by excessive solution vessel costs.

5. Discussion

5.1. Limitations

A few limitations of the proposed measures, AlignmentA,B, degree of misalignment (DoM) and individual expectation fulfillment index (IEFI) must be discussed in more detail. First, the two proposed measures assessing the alignment of expectations are limited to factor misalignment, so they do not consider the scale of the expectations. The reason to do this simplification is the fact that by including the scale, we may see the over-fulfillment of some expectations being compensated for by the underfulfillment of others, so the final measurement may be not representative of the real misalignment between the pair of stakeholders. It is argued in this paper that the use of a simple binary scale [0,1] gives a better appreciation of misalignment, avoiding such misinterpretations. Secondly, and following a similar reasoning, the IEFI measure does not consider the over-fulfillment of expectations as a positive or negative fact. It only considers if the expectation, in numerical terms, is fulfilled or not. Considering underfulfillment and over fulfillment of expectations in terms of scale would generate misinterpretations of the real fulfillment of expectations when assessed at a stakeholder level. Alternatively, and as a complement, we propose the use of goodness-of-fit (GoF) indices to measure the fit of alternative design solutions to initial design expectations (Ulstein and Brett 2015). The GoF index as a complement to our IEFI would give additional information regarding how close or far away is a specific expectation of being fulfilled. In other words, how well the final design solution fulfills the initial expectations of the stakeholders.

Another limitation of our work is the assumption of consistent behavior at the stakeholder level. This assumption is based on the theory of teams proposed by March (1994). We consider in our analysis that all the parties within a stakeholder - company, organization, or group - will have a clear, common set of expectations. Reality shows that this assumption is rare, and in most of the cases we will find a lack of agreement on company expectations (Sull et al. 2017). Such behavior would induce additional irrationality in individual stakeholder's expectations, adding an additional layer of complexity and arise uncertainty regarding the problem at hand. As an example, the expectations from the finance department and the technical department of a shipping company are typically different when pursuing a vessel newbuilding project.

Further, the effect of “side-payments” (Nash 1953) or compensations (Kaldor 1939) as an alternative to compensate requirement misalignment would be an interesting study. As a more recent example, Franssen and Bucciarelli (2005), building on the principles of Game Theory, suggest that by allowing interaction among stakeholders, these can identify collective optimal decisions and reach them rationally by means of bargaining. Understanding the relationships among the different stakeholders could facilitate and guide stakeholders during the negotiation process in this direction. For example, building on the case study of this paper, a lower fulfillment of requirements to the oil and gas company, as end-user, may be compensated by the payment of a lower dayrate for the service.

It has to be mentioned that the use of our metrics does not imply the fulfillment of axiomatic principles. Our work pursues the facilitation of interactions among stakeholders and the exchange of information. The set of metrics proposed can be used to identify misalignment among stakeholder’s expectations and determine when the preferences of a single stakeholder are inconsistent with the common mental model of the group.

5.2. Implications for design practices

The metrics proposed in this paper measure quantitatively the misalignment among stakeholder expectations. The first application of these measures is to verify that stakeholder expectations are sufficiently aligned. Is it worth to get involved in a project with more stakeholders if the degree of misalignment (DoM) is too high? To which degree is a stakeholder willing to compromise its individual expectations fulfillment index (IEFI)? This will suggest whether some stakeholders have inconsistent preferences or not. Further, these measures may be used as a reference to elaborate a common, realistic set of group requirements and constraints (considering the limitations imposed by axiomatic design), and second, as evaluation criteria for the reduction of the design space, reducing the number of design alternatives to be further assessed by decision makers. The set of measures proposed, although simple, are useful and easy to understand, which simplifies its applicability outside academic environments. Designers can utilize DoM and IEFI as communicative factors towards the customer and other stakeholders, especially to reflect the consequences in the design of misaligned expectations.

Further, the multi-stakeholder problem could be interpreted as a single stakeholder problem with alternative scenarios, operations, or preferences. As such, each stakeholder would be modeled as the representation of the single stakeholder in a potential scenario. Hence, the designer could get a better understanding of the effects of adding an additional potential scenario to the design. Similarly, a design company could exploit this methodology in new product development, by considering as stakeholders, the groups of potential customers with common expectations. Hence, the designers could take more informed decisions regarding the level of generalization they want to include in the design.

From the experience and the results gained in this case study, we have considered integrating the DoM and IEFI as an expansion of the current Ulstein ABD process. We expect to strengthen the handling of misalignment of expectations in a multi-stakeholder vessel design problem, and therefore, improve the effectiveness of the design process.

6. Conclusion

The growing interest of the industry for more effective projects and product development initiatives involving multiple stakeholders suggest the need for research on methodology capable of handling misaligned expectations. Such multi-stakeholder problems can result in overspecified designs, which can have negative ramifications in engineering design solution performance. The overall goal of this paper is to present a set of metrics supporting the negotiation of expectations among stakeholders, which should facilitate the definition of a common set of requirements and constraints satisfying all the stakeholders.

Ship design is by nature a multi-stakeholder problem. In many cases, the design process is unnecessarily prolonged due to a lack of clarity of the problem at hand. As each stakeholder has its own perception of what is needed and what to expect, the ship design process may end up on a long spiral process with continues modifications. Our methodology looks for facilitating the common understanding of the problem at hand, which is supported by a set of metrics and tools. It is far from been an all-encompassing model rather it should be seen as a complementary tool to existing approaches in the early phase of the vessel concept design process, such as Ulstein's ABD.

This paper shows the applicability of two measures to evaluate the misalignment among stakeholders' expectations and a third measure to evaluate the fulfillment of expectations as a tradeoff with costs. By applying these measures to a design case of an offshore construction vessel with four stakeholders, we show that the identification of misalignments can support a better, more informed selection of requirements and constraints, and therefore design alternatives in engineering design, and more specifically conceptual ship design.

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Main Article 3

The value of information in conceptual ship design

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Abstract

In this paper, we explore the value of information in conceptual ship design, and how it affects the way conceptual ship design takes place. Value of relevant information is an essential measure in the design of more effective ship design processes. We argue that effective information collection, storage, retrieval and use has a substantial impact on the way ship design processes should be carried out and, consequently, their effectiveness. This article proposes the use of the concept *value of information* to support the design of the ship design process; the distribution of resources between exploration and exploitation activities, and what analyses and tools should be used and when. To support our argumentation, we present the experiences from the development of a factory stern trawler design. Three typical design decisions are explored and we exemplify how the concept of value of information can be used to guide the ship designer on her decisions.

Keywords:

Ship design, information, uncertainty, exploration, exploitation

This Article is awaiting publication and is not included in NTNU Open

Main Article 4

How uncertainty influences decision-making effectiveness in conceptual ship design processes

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BACKGROUND: Understanding how and why the development of conceptual ship designs sometimes become ineffective is essential for ship design firms. Our proposition is that in many projects, uncertainty influences negatively the effectiveness of the decision-making process.

OBJECTIVE: The objective of this article is to quantify the perception of uncertainty in conceptual ship design processes.

METHODS: In this article, we propose a research model to study such a phenomenon. The research model is tested using multivariate regression analysis, building on a survey conducted among 23 shipping companies.

RESULTS: Our model suggests that 14% of the variability in the effectiveness of decision-making processes in ship design can be explained by changes in the perception of uncertainty. We can extract three interesting insights from this research work for the ship design practitioners as to how to improve the effectiveness of their design processes: (i) put more effort into the contextual factors affecting the ship design process, (ii) improve the communication with vessel owners and other stakeholders, and (iii) improve the agility of the design process.

CONCLUSIONS: This study contributes to research on uncertainty in ship design processes by: (a) proposing an investigative model, (b) developing and testing a survey instrument and (c) running a multivariate regression analysis to study the effect of perceived uncertainty on the effectiveness of decision-making processes in conceptual ship design.

Keywords:

Uncertainty, Ship design, Decision-making effectiveness, multivariate regression analysis, survey

This Article is awaiting publication and is not included in NTNU Open

Appendix G – Supporting articles

Supporting article I:

Jose J. Garcia, Carl F. Rehn, Sigurd S. Pettersen, Ali Ebrahimi, Handling Commercial, Operational and Technical Uncertainty in Early Stage Offshore Ship Design, *Proceedings of the 11th Systems of Systems Engineering Conference*, Kongsberg, Norway, June 2016.

Supporting article II:

Jose. J. Garcia, Ulrikke B. Brandt and Per O. Brett, Design for Safety in a Competitiveness Perspective, *Proceedings of the 6th Design for Safety Conference*, Hamburg, Germany, November 2016.

Supporting article III:

Jose J. Garcia, Ulrikke B. Brandt and Per O. Brett, Unintentional Consequences of the Golden Era of the Offshore Oil & Gas Industry, *Proceedings of the 1st International Conference on Ships and Offshore Structures*, Hamburg, Germany, September 2016.

Supporting article IV:

Jose J. Garcia, Per Olaf Brett, Andre Keane, Ali Ebrahimi Quantifying the Effects of Uncertainty in Vessel Design Performance – A Case Study on Factory Stern Trawlers, *Proceedings 13th International Marine Design Conference*, Turku, Finland, June 2018.

Supporting article V:

Carl F. Rehn, Jose J. Garcia, Stein Ove Erikstad, Richard de Neufville, Versatility vs. Retrofittability Tradeoff in Design of Non-transport Vessels, *Ocean Engineering*, 167(1), 2018, pp.229-238.

Supporting Article I

Handling Commercial, Operational and Technical Uncertainty in Early Stage Offshore Ship Design

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Abstract
In this paper, we assess state-of-the-art methods for handling aspects of technical, commercial and operational uncertainty in the early stages of offshore ship design. Uncertainty affects the lifecycle performance of a ship in a complex manner, which is difficult to assess in the early design process. We approach this problem by decomposing uncertainty into technical, commercial and operational aspects, and investigate how it can be identified, modelled and handled. Methods discussed include design structure matrix, tradespace exploration and evaluation methods, real options theory, stochastic optimization, and system dynamics. Strategies for handling uncertainty discussed include margins, and specific system lifecycle properties "-ilities". We argue that a decomposition of uncertainty facilitates the use of current methods and approaches for decision-making in early stage ship design.

Keywords: System Engineering, Ship Design, Uncertainty, Ship Life Cycle, Flexibility, Decision-Making

Supporting Article II

Design for safety in a competitiveness perspective

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Abstract

This paper discusses the current practice of handling uncertainties and risks by the use of extra-margins in offshore service vessel design and construction and its consequences for design complexity and cost - what is the right balance between an adequate safety level and cost-effectiveness from a competitiveness standpoint?

The current market situation characterized by a lower oil price, has strongly urged owners and designers of offshore vessels to contribute to the improvement of the overall competitiveness level of the offshore oil & gas (O&G) industry. A reasonable solution-proposition is therefore, to critically start questioning the setting of and evaluating the consequences and implications of such safety factors and uncertainty margins within the ship design and shipbuilding processes. It is argued in this paper that as a consequence of the "golden era" the trend in design and construction strategies has become: "More is better", where margins have been added to prepare for almost any uncertainties and eventualities.

Safety and uncertainty margin setting has been one of the most traditional and common ways of catering for uncertainties in the design and construction of ships. Such safety and uncertainty margins are set to handle both the absolute level of, for example, safety as well as compensating for uncertainties in the analysis of and assumptions of boundary conditions given for such complex design and construction tasks.

The safety requirements from classification societies and IMO have in most cases and over the years increased in order to improve the absolute safety level onboard vessels. In some cases it has also been introduced to cater for uncertainties in the pre-conditions for analyses and work practices. But what is really a good enough safety level? How much uncertainty and eventualities should be catered for? Is the industry willing to pay for reaching a "zero" accidents level of safety? Higher accuracy of analyses and higher fidelity of boundary conditions should perhaps lead to a reduction in such uncertainty margin practice. Are the safety margins applied in the correct way or in the right place, reflecting recent years accident statistics? Introducing a new competitive design strategy for offshore service vessels where "Good is good enough" is argued in this paper. This paper readdresses the topic and critically scrutinize current industry practices and suggests new avenues for more effective vessel design solutions.

Supporting Article III

Unintentional consequences of the golden era of the Offshore Oil & Gas industry

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Abstract
The offshore oil and gas industry has experienced an outstanding evolution over the last 10-15 years in terms of a significant number of turnouts of novel, innovative and advanced vessel design solutions being build. One important enabler for this development has been the "golden era" with an average Brent oil price hovering around 90-110 USD/bbl and worldwide exploration and production (E&P) spending being historically at very high levels for almost a decade. The golden era introduced new design strategies, market understandings, break-even rates etc. and nobody or very few has actually questioned the vessel design trend and its cost level growth consequences. A new era with significant lower oil prices have commenced and the need for a more competitive vessel design development practice needs to be established in the industry. The time has come where the unintentional consequences of the golden era must be reversed and vessel design practices be adjusted accordingly.

Keywords: Offshore vessel design; design perspectives; competitiveness; design and market uncertainty

Supporting Article IV

Quantifying the effects of uncertainty in vessel design performance - A case study on factory stern trawlers

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Abstract

A quantitative evaluation of the effects of uncertainty surrounding the development of the next generation of factory stern trawlers is suggested as progression of state-of-the-art ship design practice. To better understand and take into consideration the uncertainties related to the technical, operational and commercial aspects influencing the solution space definition of a factory stern trawler is paramount. This paper discusses such a challenge and reviews ways in which current ship design practice and vessel design solutions developed thereof, can be improved and implemented in novel ship design approaches. The fifth generation of factory stern trawlers – focusing on improving energy efficiency and food product quality - is currently under development, drenched in a deluge of uncertainty. With an aged fleet with little renovation and renewal since the early 90s, the need for greener and more commercially effective vessels has spurred a fleet renewal market trend. The evolution of technologies and their future benefits, new regulations regarding fishing quotas, fish quality or fish processing, or the future availability of fish among others, have demonstrated, historically, to play an important role on fishing vessel performance. We, therefore, propose new methods of quantification of their effects to improve the performance of the vessel design of the next generation stern trawler.

The research behind this paper is based on a methodology of structured accelerated business development (ABD) workshops identifying uncertainty factors, which are contrasted with those found in state-of-the-art literature. A MATLAB-based simulation model to quantify their effects on the economic performance of the vessel is developed and reviewed in this paper. This model is presented and discussed. The paper argues that a better understanding of the effects of uncertainty factors in the design and operation of factory trawlers, and all other vessel types, for that matter, should support more effective decisions and a better vessel design work process. The paper presents, therefore, a tool to support decision-making under uncertainty during both, the conceptual design phase and in the operational phase of the vessel.

Supporting Article V

Versatility vs. retrofittability tradeoff in design of non-transport vessels

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Abstract
In this paper, we study the relationship between economic performance and flexibility for non-transport vessels. More specifically, we investigate the difference between two means of achieving flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs with or without change of physical form, respectively. A model is presented to study this relationship, where we first generate design alternatives with relevant, flexible properties before we subsequently evaluate the design alternatives based on their expected discounted economic lifecycle performance. The evaluation model is based on a two-level decomposition of the planning horizon to handle temporal complexity, using scenario planning and Epoch-Era analysis (EEA) for long-term strategic considerations, and Monte Carlo simulation and optimization for medium-term tactical ship deployment. The proposed model is applied to an offshore construction ship design case. Findings indicate that retrofittability can increase economic performance significantly for non-transport vessels operating in an uncertain heterogeneous context.

Keywords: ship design, retroffitability, versatility, flexibility, uncertainty

Appendix H- Previous PhD theses published at the Department of Marine Technology

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)
UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups

UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
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UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
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MTA-2001-147	Heggelund, Svein E., MK	Calculation of Global Design Loads and Load Effects in Large High Speed Catamarans. (Dr.Ing. Thesis)
MTA-2001-148	Babalola, Olusegun T., MK	Fatigue Strength of Titanium Risers – Defect Sensitivity. (Dr.Ing. Thesis)
MTA-2001-149	Mohammed, Abuu K., MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
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MTA-2002-151	Rognebakke, Olav F., MH	Sloshing in rectangular tanks and interaction with ship motions. (Dr.Ing. Thesis)
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MTA-2002-157	Ge, Chunhua, MK	Global Hydroelastic Response of Catamarans due to Wet Deck Slamming. (Dr.Ing. Thesis)
MTA-2002-158	Byklum, Eirik, MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
IMT-2003-1	Chen, Haibo, MK	Probabilistic Evaluation of FPSO-Tanker Collision in Tandem Offloading Operation. (Dr.Ing. Thesis)
IMT-2003-2	Skaugset, Kjetil Bjørn, MK	On the Suppression of Vortex Induced Vibrations of Circular Cylinders by Radial Water Jets. (Dr.Ing. Thesis)
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IMT-2009-45	Amlashi, Hadi K.K.	Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD Thesis, IMT
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IMT-2009-48	Ong, Muk Chen	Applications of a Standard High Reynolds Number Model and a Stochastic Scour Prediction Model for Marine Structures. PhD-thesis, IMT
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IMT 2009-55	Holstad, Anders	Numerical Investigation of Turbulence in a Sekwed Three-Dimensional Channel Flow, Ph.d.-thesis, IMT.

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IMT 2010-58	Kristiansen, David	Wave Induced Effects on Floaters of Aquaculture Plants, Ph.d.-thesis, CeSOS.
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IMT 2010-60	Hals, Jørgen	Modelling and Phase Control of Wave-Energy Converters. Ph.d.thesis, CeSOS.
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IMT 2010-63	Califano, Andrea	Dynamic Loads on Marine Propellers due to Intermittent Ventilation. Ph.d.thesis, IMT.
IMT 2010-64	El Khoury, George	Numerical Simulations of Massively Separated Turbulent Flows, Ph.d.-thesis, IMT
IMT 2010-65	Seim, Knut Sponheim	Mixing Process in Dense Overflows with Emphasis on the Faroe Bank Channel Overflow. Ph.d.thesis, IMT
IMT 2010-66	Jia, Huirong	Structural Analysis of Intect and Damaged Ships in a Collission Risk Analysis Perspective. Ph.d.thesis CeSoS.
IMT 2010-67	Jiao, Linlin	Wave-Induced Effects on a Pontoon-type Very Large Floating Structures (VLFS). Ph.D.-thesis, CeSOS.
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IMT 2011-69	Karimirad, Madjid	Stochastic Dynamic Response Analysis of Spar-Type Wind Turbines with Catenary or Taut Mooring Systems. Ph.d.-thesis, CeSOS.
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IMT-2011-81	Chen, Qiaofeng	Ultimate Strength of Aluminium Panels, considering HAZ Effects, IMT
IMT-2012-82	Kota, Ravikiran S.	Wave Loads on Decks of Offshore Structures in Random Seas, CeSOS.
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IMT-1-2014	Song, An	Theoretical and experimental studies of wave diffraction and radiation loads on a horizontally submerged perforated plate, CeSOS
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IMT-3-2014	Dai, Lijuan	Safe and efficient operation and maintenance of offshore wind farms ,IMT
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IMT-5-2014	Wang, Jingbo	Water Entry of Freefall Wedged – Wedge motions and Cavity Dynamics, CeSOS

IMT-6-2014	Kim, Ekaterina	Experimental and numerical studies related to the coupled behavior of ice mass and steel structures during accidental collisions, IMT
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Doctoral Thesis

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