Towards controlled innovation of complex objects.
A sociotechnical approach to describing ship design

van Bruinessen, Ties

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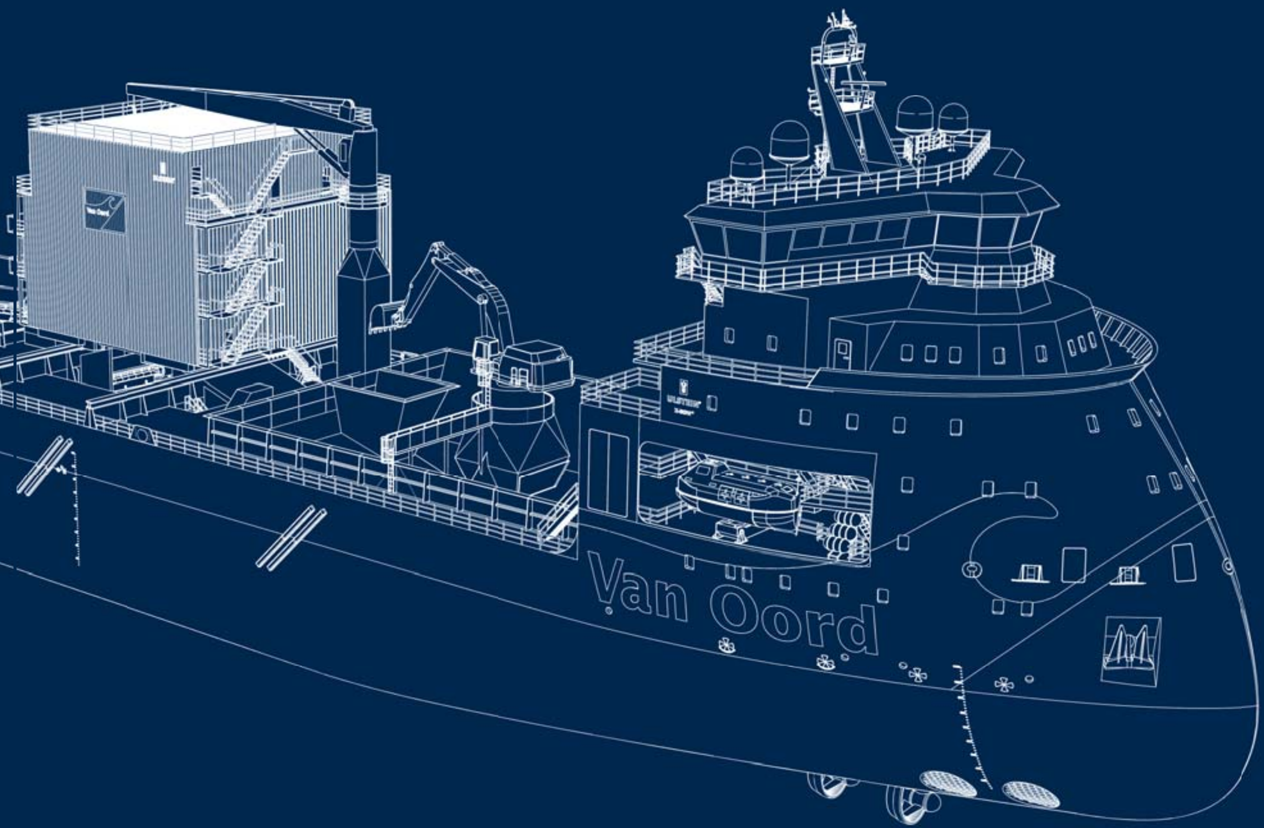
Towards controlled innovation of complex objects



Ties van Bruinessen

Propositions

accompanying the dissertation

Towards controlled innovation of complex objects
a social-technological approach to describing ship design

by

Ties. M. van Bruinessen

1. To improve innovative capacity of the complex specials industry, ship design companies should offer the client a design process in the C-space (Hatchuel & Weil, 2002), not a selection from a portfolio of existing designs.

2. The complexity of design is not only determined by the technical dimension, but at least equally as much, if not more, by the social dimension.

3. The description of the ship design process becomes more accurate when adopting the notions of coevolution (developments on multiple levels of system decomposition) as well as the social and technical interaction.

4. There will always be tension between designers and scientists: "*invention causes things to come into existence from ideas, makes the world conform to thought; whereas science, by deriving ideas from observation, makes thought conform to existence*" (Mitcham, 1978, p244). However, the Deweyan Inquiry aims to overcome this tension by supporting designers to become scientists.

5. The relevance of research in applied sciences increases when the human factor is taken into account.

6. Recent production tools, such as 3D-printing, require engineers who can design.

7. To remain a technical university of relevance, engineering curricula should increase the focus on the fundamental principles of the design process.

8. Extreme sports should be regulated by the athletes themselves.

9. If sun and wind are aligned, you never sail in your own shadow.

10. Respect and extremism are irreconcilable.

The propositions are regarded as opposable and defendable, and have been approved as such by the supervisors prof. ir. J.J. Hopman and dr. ir. F.E.H.M. Smulders

Stellingen

behorende bij het proefschrift

Towards controlled innovation of complex objects
a social-technological approach to describing ship design

door

Ties. M. van Bruinessen

1. Om tijdens het ontwerpen van complexe objecten de capaciteit van innoveren te vergroten zouden scheepsontwerpers niet een portfolio van bestaande ontwerpen moeten aanbieden, maar een ontwerpprocess gebaseerd op concepten (de C-space (Hatchuel & Weil, 2002)).

2. De complexiteit van het ontwerpen wordt niet alleen bepaald door de technische dimensie, maar minstens zoveel door de sociale dimensie.

3. De beschrijving van het scheepsontwerp proces wordt accurater wanneer de noties van co-evolutie (ontwikkelingen op meerdere niveaus van de systeemdecompositie), sociale en technische interactie worden meegenomen.

4. Er zal altijd spanning zijn tussen ontwerpers en onderzoekers: "*het uitvinden zorgt ervoor dat er objecten ontstaan van ideeën: het past de fysieke wereld aan op basis van de gedachte. In de wetenschap, waar nieuwe ideeën ontwikkeld worden door observaties, past men de gedachten aan op basis van de fysieke wereld*" (vertaald van: Mitcham, 1978, p244). De Deweyan Inquiry tracht deze spanning weg te nemen door ontwerpers te ondersteunen in het wetenschappelijke veld.

5. De relevantie van onderzoek in de toegepaste wetenschappen neemt toe wanneer de menselijke factor in acht word genomen.

6. Voor het gebruik van recent ontwikkelde productiemogelijkheden zoals 3D printen heb je ingenieurs nodig die kunnen ontwerpen.

7. Om als technische universiteit relevant te blijven, moeten ingenieursopleidingen ook de fundamentele principes van ontwerpen onderwijzen.

8. Extreme sporten moeten gereguleerd worden door de atleten zelf.

9. Als de zon en de wind uit dezelfde richting komen, vaar je nooit in je eigen schaduw.

10. Respect en extremisme zijn onverenigbaar.

Deze stellingen worden oppeneerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor en co-promotor prof. ir. J.J. Hopman en dr. ir. F.E.H.M. Smulders

Towards controlled innovation of complex objects

a sociotechnical approach to describing ship design

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft;
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties

in het openbaar te verdedigen op woensdag 25 mei 2016 om 12:30 uur

door Ties Marijn van BRUINESSEN

Scheepsbouwkundig ingenieur
geboren te Aardenburg

Dit proefschrift is goedgekeurd door de
promotoren: Prof. ir. J.J. Hopman en Dr. ir. F.E.H.M. Smulders

Samenstelling promotiecommissie:

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Prof. ir. J.E. Oberdorf	TU Delft, Delft
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Preface

This book is a PhD thesis. Within this thesis I strive to describe and improve the way naval architects develop innovative ships and other complex systems. Developing innovative designs does not only require technical knowledge, but also requires insight in the technical and social interaction with other actors during the design process. Ship designers are often expected to develop knowledge about the social and technical interaction through experience, and as such, the industry is dependent on the ad hoc application of such skills. This research could not have been conducted without a strong influence and interaction with the current practice to review the current state-of-the-art, but also to reflect and test new ideas on describing these activities.

The idea to improve understanding of ship design was an important part of my study time in Delft, after my MSc graduation the university gave me the opportunity to write these ideas down, and discuss this with people within industry. One of my first meetings was with Jeroen Lusthof, at the time technical manager and owner of Ulstein Sea of Solutions (since 2015 the name changed to Ulstein Design & Solutions BV, but within this dissertation it is referred to as USoS), during this introductory meeting, we discussed the challenges he saw in the industry which aligned almost fully with the challenges I saw and had written down. Based on this discussion, Ulstein Sea of Solutions offered to hire me, and support this dissertation throughout the last 5 years, the result of which is now in front of you.

During the research described in this book I had the opportunity to interview, talk to, work besides and have discussions with several of the most gifted ship designers in our industry. Only with their support I was able to improve my own understanding of ship design considerably, but hopefully also, by writing this book, improve your understanding. Throughout the book you will find a combination of theory, observations from practice and my own developments. I hope you will see these texts as a challenge: not only to improve your own practice, but also to develop, voice and write down your ideas. In that case, please let me know!

Ties van Bruinessen
Rijswijk, April 13th, 2016

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Summary

Within the ship design industry, and in particular in the development of large, complex and innovative vessels experienced ship designers play an important role in organizing and structuring the design process. How this actually happens within projects that develop such large, complex and innovative vessels for a single client is not clear. This observation lead to a broad, initial research question as the starting point for further research.

How are innovative, large and complex vessels developed in practice?

Because of the broad, explorative nature of this research question it was not possible to apply a research strategy aimed on justification and validation, an approach more common in ship design. After the evaluation of several alternatives a Deweyan inquiry was selected as most promising for this research, as it allowed for the parallel development of theory and practice in a pragmatic approach.

One of the first steps was to provisionally pinpoint and frame the initial doubtful situation based on observations in both theory and practice. The current state-of-the-art ship design literature was analysed to determine the creative elements in each design strategy. To enable this analysis CK theory was applied. CK is an approach introduced as a unifying theory to describe creative design, it differentiates between two distinct 'spaces' with their own rules and logic: the Knowledge space, which is based on propositions that are either true or false and the Concept space, where propositions are still undetermined and can either be true or false. To describe creative design, a design process should describe steps from the knowledge space into the concept space and vice versa.

The analysis showed that the majority of design processes do not describe the full scope of creative activities, but only concentrate on parts of the ship design process. Creative ship design, system based design and requirement elucidation explore a broader scope of the ship design process, concentrating full creative design of the overall ship design, or in the case of requirement elucidation of both the requirements and the ship design.
To analyse the four case studies CK theory was complemented by the system thinking perspective observed in literature. Both were applied to analyse the development of four vessels: the SWind1000, the Greenstream, the Bourbon Orca and the Pioneering Spirit. In each of these case studies the project did not concentrate on a single level of decomposition (a focus on either the business case, the ship design, the system design or component design) but developed multiple levels of decomposition in parallel. For example, in the development of the Bourbon Orca, the project team worked on the hull design, the deck equipment and the propulsion system (system level) in parallel with the overall layout of the vessel (ship design level).

This phenomena, called 'coevolution' between solutions on different levels of decomposition appears to be a key part in innovative ship design, allowing creative solutions to develop and influence each other. These creative developments often occur within different companies or different departments of the same company, resulting in considerable interaction between the involved actors.

During the analysis of the development of the four vessels, complemented with a series of interviews and an additional reference case it became clear that one of the most important roles of the experienced ship designers was to handle and manage the interaction between different actors caused by coevolving solutions. There were two dimensions to this interaction: the technical dimension illustrates the content of the interaction, the social dimension concentrates on the way the information is transferred. Based on these observations and an initial choice to explore the technical dimension of the interaction the following constructive hypothesis was developed, as a starting point to evaluate the observations made in both practice and theory:

To improve the development of coevolving innovative solutions a design process should focus on two levels of decomposition, allow for weak system boundaries and take into account the technical dimension (the content) of the interaction.

In practice, experienced naval architects are more than capable of developing innovative solutions. However, to improve such processes more control would be preferable without constraining the initiation of creative solutions. Based on the initial review a more controlled process should include the following elements: the definition of potentially innovative solutions, the involvement of technology partners and other actors, support the integration and coevolution within weak boundaries and manage the timing of creativity.

To develop a design strategy capable of taking the technical dimension of the interaction into account, a model was necessary that describes cohesion within a system of systems. This model could in a later stages be used as a template for a design strategy.

The model to determine the cohesion in a system-of-systems is based on the individual system description using the aspects Form, Characteristics, Performance and Function, which is the same on each level of decomposition. Five relations were determined outside the system boundaries: decomposing and integrating a system (the form of system X – the form of system X-1 and vice versa), the contextual influence (form of system X – characteristics of system X-1) and the performance – function cohesion (function of system X – performance of system X-1 and vice versa). This results in the overall model of the cohesion shown in figure 1.

The model of cohesion was used as a template to develop a design strategy taking the technical dimension of the interaction into account. The strategy developed in this research starts from a required ship functionality (the objective), which is developed into different sets of system performance parameters, which lead to the individual system developments. In a later stage, these individual system developments are integrated into the overall ship design and evaluated (figure 2). This is a departure from the conventional approach within the ship design industry, which often starts from an existing general arrangement.

The design strategy was applied during the development of two Ulstein Design & Solutions B.V. (formerly known as Ulstein Sea of Solutions, USoS) vessels: the Ulstein

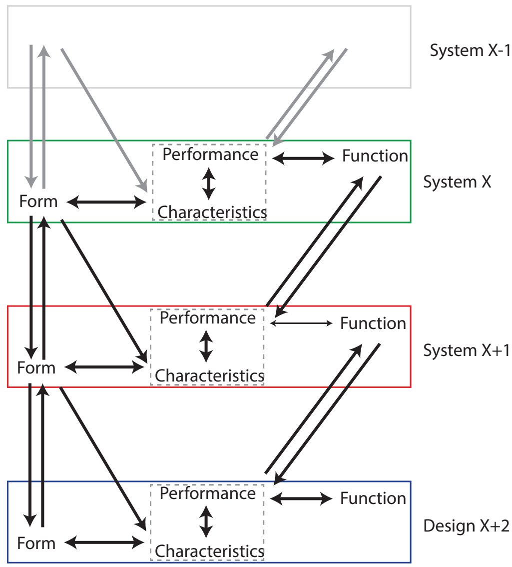


Figure 1. The model of cohesion

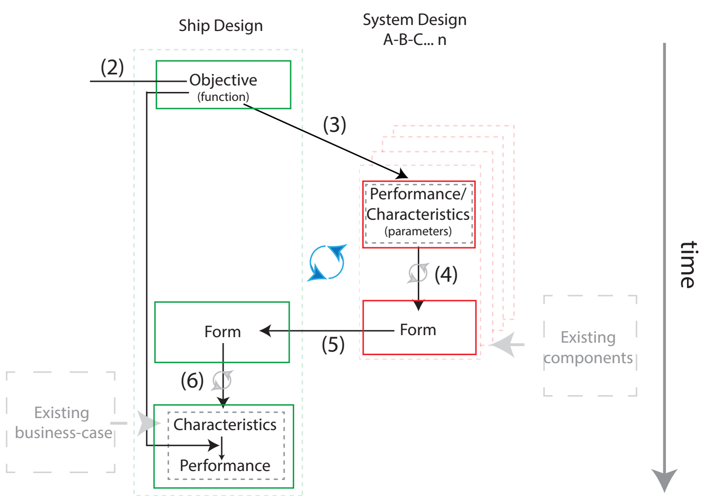


Figure 2. The design strategy, based on the interaction between system and ship design

AXDS, an arctic drillship developed for Statoil and the Bravenes, a subsea rock installation vessel developed for Van Oord. The first project was developed with active influence of the researcher, as I was involved as a naval architect and design process guardian. The second project was provided with the initial documentation, but was not actively influenced by my involvement.

The application of an explicit design strategy had a considerable effect on both projects. Both designs were considered very innovative without major showstoppers. Even though there are only two projects available, the design strategy still appears to have a positive influence on defining innovative solutions, the structured involvement of technology partners and the integration and coevolution of new solutions as well as the timing of creativity in the process. For this particular purpose, the design strategy was well suited, relevant and provided a workable and sufficient flexible solution. This confirmed the idea that design strategies that take coevolving solutions and the technical dimension of interaction into account provide a better description of the innovative ship design process.

During the hypothesis and model development in this research the social dimension of the interaction was not taken into account. During the experiments the role of this social dimension became more evident, as the explicit design strategy required different actors to think and discuss their role within the project. For further research, a proposal is developed to explore the social dimension of the interaction between actors in the design process, as a new starting point or 'doubtful situation' in further research. Such a research could for example concentrate on boundary objects, process models or synchronizing activities.

This research explored the way experienced ship designers develop innovative solutions, it revealed that the current ship design methods insufficiently describe the process of coevolving solutions, including the interaction between the different actors that result from this. This dissertation does not result in a complete prescriptive method to control innovative design, but it explores, identifies and evaluates the key parameters that should be taken into account in such approaches.

Samenvatting

In de scheepsontwerp industrie en specifiek in de ontwikkeling van grote, complexe en innovatieve schepen spelen ervaren scheepsontwerpers een belangrijke rol in het organiseren en structureren van het ontwerpproces. Wat er precies gebeurd tijdens dergelijke projecten, waar dergelijke schepen voor een specifieke klant zijn ontwikkeld is niet duidelijk. Deze observatie leidde tot een initiële onderzoeksvraag als startpunt voor verder onderzoek:

"hoe worden innovatieve, grote en complexe schepen in de praktijk ontwikkeld?"

Door de brede onderzoeksvraag was het niet mogelijk een onderzoeksstrategie te gebruiken die verificatie en validatie als doel heeft, de gebruikelijke aanpak binnen scheepsontwerp onderzoek. Na een evaluatie van verscheidene alternatieven is er gekozen voor een Deweyan Inquiry, een aanpak die het meest waardevol leek door de parallelle ontwikkeling van theorie en praktijk in een pragmatische aanpak.

Tijdens de eerste stap worden de uitdagingen in de originele situatie vastgesteld en ingekaderd, gebaseerd op observaties in zowel de theorie als de praktijk. Van de huidige state-of-the-art scheepsontwerp literatuur is geanalyseerd in hoeverre ze creatieve ontwerpprocessen beschrijven. De analyse is gebaseerd op CK theorie, een aanpak die geïntroduceerd is als een overkoepelende theorie om creatief ontwerpen te beschrijven. CK theorie maakt onderscheid tussen 2 'ruimtes', elk met eigen regels en logica: de kennisruimte (K-space), gebaseerd op het idee dat alle voorstellen die waar of onwaar zijn, en de conceptruimte (C-space), waar voorstellen nog onbepaald zijn en zowel waar als onwaar kunnen zijn. Om creatief ontwerpen te beschrijven zou een ontwerpproces de stappen moeten beschrijven van de kennisruimte richting de conceptruimte gaat en vice versa.

De analyse laat zien dat het merendeel van de scheepsontwerpprocessen niet het volledige creatieve proces beschrijven, maar zich concentreren op een klein deel van het ontwerpproces. Creative ship design, system based design en requirement elucidation verkennen een bredere scope en bespreken het creatieve ontwerp van het overall schip of, in het geval van requirement elucidation, op de ontwikkeling van het scheepsontwerp en het pakket van eisen.

Parallel aan de literatuuranalyse is er een analyse gedaan van de ontwikkeling van vier innovatieve schepen: de SWind1000, de Greenstream, de Bourbon Orca en de Pioneering Spirit. Dit is gedaan op basis van CK theorie, aangevuld met systeem theorie. De ontwikkeling tijdens deze projecten concentreerde zich niet op een enkel niveau van decompositie (businesscase, scheepsontwerp, systeem ontwerp of component ontwerp), maar tijdens elk project werden er meerdere niveaus van decompositie parallel ontwikkeld. Bijvoorbeeld gedurende de ontwikkeling van de Bourbon Orca werd er tegelijkertijd aan de rompvorm, het dek equipment, de voorstuwingsinstallatie (op systeem niveau) en het overall scheepsontwerp gewerkt.

Deze aanpak, geïdentificeerd als 'co-evolutie' tussen oplossingen op verschillende niveaus van decompositie lijkt een belangrijk onderdeel van innovatief scheepsontwerpen. Tijdens het proces worden creatieve oplossingen ontwikkeld die elkaar kunnen ondersteunen. Dit gebeurd vaak in verschillende bedrijven of verschillende afdelingen binnen hetzelfde bedrijf, maar het resulteert altijd in interactie tussen de betrokken partijen.

Tijdens de analyse van de casestudies, aangevuld met extra informatie, werd het duidelijk dat het beheersen en controleren van de interactie tussen verschillende actoren, als gevolg van deze co-evolutie, een van de belangrijkste taken is van een ervaren scheepsontwerper. De interactie tussen actoren bestaat uit twee dimensies: de technische dimensie van de interactie beschrijft de inhoud: 'wat' er gecommuniceerd wordt. De sociale dimensie van de interactie beschrijft hoe de informatie overgebracht wordt. Op basis van de observaties is er initieel gekozen de technische dimensie van de interactie te verkennen, dit leidde tot de volgende hypothese voor vervolg onderzoek in zowel praktijk als theorie:

"Om de ontwikkeling van co-evoluerende, innovatieve oplossingen te verbeteren, zal een ontwerpproces zich moeten richten op twee niveaus van decompositie, gebaseerd op zwakke systeem grenzen en daarnaast de technische dimensie (de inhoud) van de interactie tussen actoren in acht nemen."

In de praktijk zijn ervaren scheepsontwerpers zeer bedreven in het ontwikkelen van innovatieve oplossingen. Toch zou het wenselijk zijn dit proces beter te beheersen, maar zonder dat dit de ontwikkeling van creatieve oplossingen beperkt. Op basis van de review zou een beter beheersbaar proces de volgende elementen bevatten: de identificatie van mogelijk innovatieve oplossingen, het betrekken van partners en andere actoren, de integratie en co-evolutie van oplossingen binnen ontwikkelende systeemgrenzen en de timing van creativiteit in het proces.

Om een ontwerpstrategie te maken die aan deze eisen voldoet moet eerst een model gemaakt worden van de cohesie in een 'system-of-systems'. Dit model kan daarna als een template gebruikt worden voor de ontwerpstrategie. Het model is gebaseerd op een individuele systeem beschrijving met de aspecten Vorm, Karakteristieken, Performance en Functie. Deze systeem beschrijving is op elk niveau van decompositie hetzelfde.
Tussen de systemen op verschillende niveaus van decomposities zijn vijf relaties geïdentificeerd: De decompositie en integratie van een systeem (vorm van systeem X <-> vorm van Systeem X+1), de contextuele invloed (de vorm van systeem X -> karakteristieken van systeem X+1) en de samenhang tussen performance en functie (functie van system X <-> performance van systeem X+1). Dit resulteert het volledige model, gepresenteerd in figuur 1.

Het model wat de cohesie binnen een 'system of systems' beschrijft is gebruikt als een template voor de ontwikkeling van een ontwerpstrategie, zodat de technische dimensie van de interactie in acht wordt genomen. De strategie ontwikkeld in dit onderzoek concentreert op het scheepsontwerp ("system X") en de systeemontwerpen ("system X+1"). De strategie start bij de scheepsfunctionaliteit (de doelstelling van dit project) die ontwikkeld wordt in verschillende 'sets' van performance eisen. Deze sets worden ontwikkeld in individuele systeem oplossingen. In een later stadium worden deze

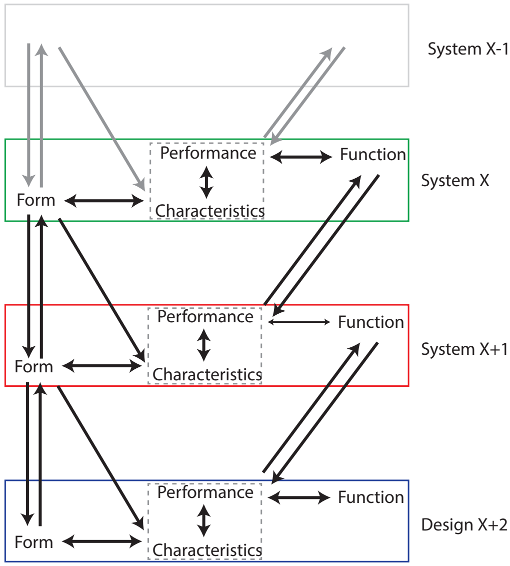


Figure 1. Het model van cohesie

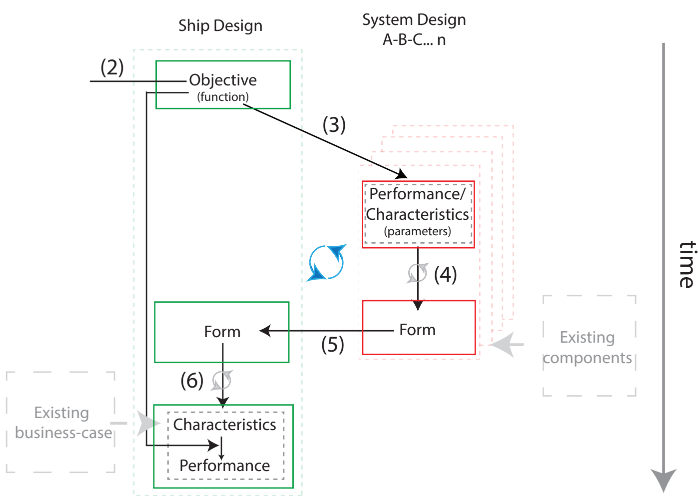


Figure 2. De ontwerpstrategie, gebaseerd op het parallel ontwikkelen van schip en systeem ontwerp

systeemoplossingen, aangevuld met bestaande kennis, geïntegreerd in het overall scheepsontwerp en geëvalueerd (figuur 2). Dit is een afwijking van de conventionele aanpak in het scheepsontwerpen, wat vaak begint vanaf een bestaand algemeen plan.

Deze ontwerpstrategie is toegepast tijdens de ontwikkeling van twee Ulstein Design & Solutions B.V. (tijdens deze projecten nog bekend als Ulstein Sea of Solutions) schepen: de Ulstein AXDS, een boorschip voor de Arctische gebieden ontwikkeld voor Statoil, en de Bravenes, een stenenstorter voor Van Oord. Tijdens het eerste project was ik actief betrokken als scheepsontwerper en ondersteuning met betrekking tot het ontwerpproces, in de het tweede project was ik niet actief betrokken.

De toepassing van een expliciet gedefinieerde ontwerpstrategie had aanzienlijke invloed op beide projecten. Beide projecten werden over het algemeen gezien als zeer innovatief, maar ook zonder grote uitdagingen. Het proces is maar getest in twee projecten, maar op basis van de analyse lijkt de ontwerpstrategie een positieve invloed te hebben op het ontwikkelen van innovatieve oplossingen, het betrekken van de juiste partners, het sturen van de integratie en co-evolutie van oplossingen en het timen van de creatieve stappen. Voor dit specifieke geval was de ontwerpstrategie toepasbaar, relevant en leverde een voldoende flexibele en werkbare oplossing. Deze observatie bevestigde het idee dat ontwerp strategieën die co-evoluerende oplossingen en de technische dimensie van interactie in acht nemen een betere beschrijving geven van het scheepsontwerpproces.

Tijdens de ontwikkeling van de originele hypothese en het daaropvolgende model is de sociale dimensie van de interactie niet expliciet meegenomen. Tijdens de interventies werd de rol van de rol van deze sociale dimensie steeds duidelijker: de ontwerpstrategie zorgde ervoor dat verschillende actoren hun rol binnen het project moesten identificeren en bespreken, waardoor deze sociale dimensie steeds beter geformuleerd kon worden. Als een startpunt voor nieuw onderzoek is er een voorstel geschreven om deze sociale dimensie tussen de actoren in het ontwerpproces verder uit te zoeken. Een dergelijk onderzoek kan zich, bijvoorbeeld, richten op boundary objects, proces modellen of synchronisatie activiteiten.

Dit onderzoek verkent de manier waarop ervaren scheepsontwerpers innovatieve oplossingen bedenken en uitwerken. In dit proces speelt de co-evolutie van oplossingen en de daaropvolgende interactie tussen de verschillende actoren een belangrijke rol: activiteiten die niet beschreven worden in de huidige scheepsontwerpmethodes. Deze dissertatie resulteert niet in een methode die een het innovatieve scheepsontwerp volledig controleert, maar het verkent, identificeert en evalueert de belangrijkste parameters die meegenomen moeten worden in een dergelijke aanpak.

Part I

The doubtful situation

Chapter 1

Introduction

"Introducing the challenges which were the starting point of this dissertation"

Innovation is a keyword in maintaining competitiveness and business development (Schumpeter, 1942). Innovation and implementing new, creative solutions do not necessarily result in successful business but without it, long-term failure is a near certainty (Cox, 2005; Howard, et al., 2008). This reflects in a wide range of research and practice; each with their own definitions and theoretical frameworks to illustrate, define, manage and describe the role of innovation within their respective fields. The need for innovation also applies to the ship design industry: it is often described as the only way to maintain competitiveness within the West-European ship design industry (Hopman, 2007), with innovating as an activity that should be at the core of all companies in the maritime industry (Wijnolst & Wergeland, 2009). The quest for innovation results in a broad spectrum of innovative vessels, ranging from ever larger container vessels, inland shipping vessels powered by LNG, innovative hull forms and complex offshore construction vessels (figure 1-1).

Figure 1-1. A broad spectrum of innovative vessels operating in the maritime industry

Such a broad spectrum of innovation in ship designs raises an interesting question: how are such innovative vessels developed? Design or innovation process models often point towards a solution with a predefined innovative content, but according to Howard and his colleague's: there are no models available that cover the different processes leading to different types of innovative solutions (Howard, et al., 2008).

Ship designers are nevertheless capable of developing innovative solutions to solve challenges in practice. The industry is very dependent on the experience of these designers to do this successfully, a challenging situation when innovating, as Lawson & Dorst show: the combination of experience and creativity necessary to develop innovative solutions are not necessarily related to one another (Lawson & Dorst, 2009). Ship design literature only sparsely discusses creative activities and inventions necessary to develop these innovative solutions (Brett & Ulstein, 2012), with the notable exceptions in the work of Andrews and McKesson (Andrews, 1981; 2004; McKesson, 2013). Still, there are no publications that provide insight in the relation between innovative content and the applied design process to develop these ships.

Creativity and innovation in the development of large ships has considerable impact on the business of ship design. For example, clients and ship designers often prefer a design strategy based on modifying and improving an existing vessel: an approach which only takes a limited amount of time, resources and feels intuitively safe (Keane & Tibbits, 2013). However, as both Evans and Keane & Tibbits illustrate, when developing an innovative solution using a "parent" design might lead to considerable problems. At the very least, such an approach is counterproductive when developing innovative solutions for new challenges (Evans, 1959; Keane & Tibbits, 2013).

This book reports on a PhD-research exploring these initial observations. This chapter provides the context required to define the initial research question of this research, defining the boundaries of this research based on the current practice (1.1), provide a first glance at the available design processes (1.2) and to explore both creativity and innovation (1.3, 1.4), before the initial research question in section 1.5 (figure 1-2).

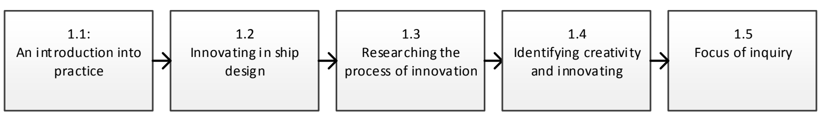


Figure 1-2. An overview of chapter 1

1.1 An introduction into practice

The West-European ship design industry is an interesting business area to conduct this research in: large, complex and integrated vessels are developed within a relative short time frame. Different companies are involved in the operation, ship design, system design, component design, production, classification and ownership, with each involvement different in time and structure.

The wide range of companies involved in the development process also results in a variety of clients for ship designers: clients range from end users such as governments or oil companies (Jacobsen & Håland, 2013), to owners who want to expand their fleet (Heerema, 2014), ship financers that build vessels on speculation (Tradewindsnews.com, 2014) or equipment manufacturers that develop designs around new equipment (Ulstein, 2013). These clients not only differ in their inherent activities but are located all over the world: the industry is truly global (Hopman, 2007). The global nature and variety of clients results in a wide range of companies and agencies involved as ship designers.

New vessels are developed in-house by operators (Allseas, 2014), shipyards (Royal IHC, 2014), equipment manufacturers (Huisman Equipment B.V., 2008; Wärtsilä, 2014), or independent design offices (Ulstein Sea of Solutions, 2012a; Salt Ship Design, 2013). This makes the industry unique: in each project the combination of involved actors, culture, priorities, background and requirements is different.

Within this industry each ship design is modified, adapted or developed by ship designers for a specific client: a client with their own objectives, equipment and operational preferences. In some cases this results in new ship designs, while more often an existing design was used with minor or major modifications. The different objectives lead to the broad spectrum of vessels shown in figure 1-1.

Hopman shows that the West-European industry is specialized in tailor-made vessels implementing new and high-value technologies, physically large and one-off, often identified as complex specials (Hopman, 2007). These vessels are complex because they are not only structures but vehicles as well, continuously entering different environments (Evans, 1959) making it difficult to determine their performance (Gaspar, 2013). Furthermore, they are influenced by a trade-off between economical and technical performance (Levander, 1991). The size of these vessels makes it impossible to develop full-size prototypes, therefore the consequences of failures in these new technologies are very high (Andrews, 2013). In general, designs are developed based on an existing vessel to manage apparent risks, resulting in evolutionary but not revolutionary change. Improving product innovations in large and complex vessels, supporting a specific client's objectives, equipment and operational preferences may be improved when generating more insight in the role of developing innovations.

1.2 Innovating in ship design

The West-European ship design branch modifies, adapts or develops vessels for each individual client. How innovative vessels are developed within this industry is explored by illustrating where creative and innovative developments take place, who are involved (1.2.1) and how this is currently managed (1.2.2).

1.2.1 Defining innovating in ship design

The wide range of different clients and companies involved in ship design not only have an impact on the resulting vessel, but also influences when innovative solutions are implemented, ranging from the initial concept development to changes on vessels already in operation. Product innovations are even implemented while refitting the vessel (Allseas, 2014) or in vessels under construction (Maslin, 2013). Still, the majority of product innovations are developed during the early stages of the development (Hopman, 2007). At this stage the freedom to make changes is considerable, making it possible to have significant influence on the design (Dierolf & Richter, 1989), (figure 1-3).

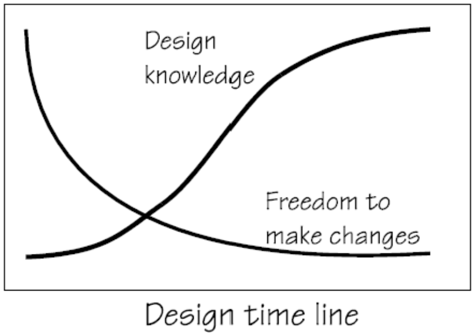


Figure 1-3. Design time versus design freedom and knowledge of a specific design (Erikstad, 1996)

The initial phases of product development, often called the feasibility study or conceptual design phases, allow for considerable changes because of the limited constraints. At the same time, the development lacks project specific design knowledge (Erikstad, 1996), (figure 1-3). Still, these initial phases are considered critical in the development of innovative, large and complex vessels (Hopman, 2008; Andrews, 2013). These early phases are remarkably short: derivative designs are developed by a limited number of people in a matter of weeks, while vessels with considerable innovations are developed within months.

Erikstad shows that such projects are, in general, managed using a shallow knowledge structure and strong domain tradition: the experience and judgement of the ship designers supported by the organisational structure of the involved companies (Erikstad, 1996). The majority of innovative activities related to product innovations occur in the early stages of the development, often identified as the feasibility or conceptual phases. These activities are developed by experienced ship designers within an open, informal and flexible organisational structure in a very short timeframe.

1.2.2 Developing innovative vessels

Keane & Tibbits (2013) generalize towards two approaches available in the early stages to develop new ship designs: a derivative design based on a parent design or a new design starting from a blank sheet of paper. The derivative design approach, or the development from a parent design, is often selected by client and ship designer as it is believed such an approach has few technical risks (ibid.), resulting in a manageable project with limited costs. It is not surprising that such approaches, often represented as the design spiral (figure 1-4) are relative well known. The original definition of the approach starts with a known general arrangement (GA) and propulsion arrangement that is modified to comply with the requirements of the client (Evans, 1959). Other versions of the design spiral are modified to initiate product development from owner requirements (Gale, 2003), design concepts (Hopman, 2007) or economic considerations (Buxton, 1972). The iterative approach continuously increases the level of detail while balancing the different elements of the design. The approach is developed for situations where changes to the original 'parent' are small (Evans, 1959), but can cause considerable problems when the requirements of the client and new technologies do not suit the original general arrangement (Andrews, 2004; Keane & Tibbits, 2013).

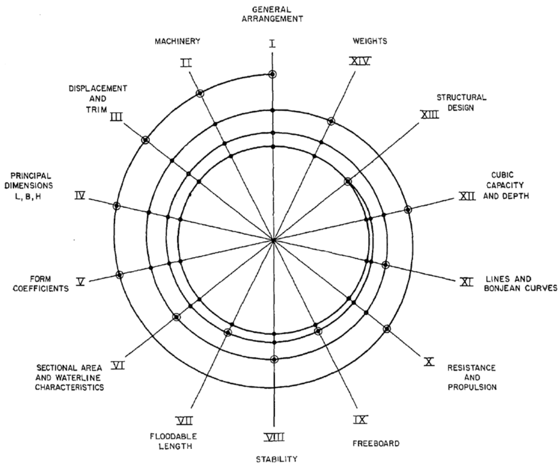


Figure 1-4. Design spiral (Evans, 1959)

The blank sheet of paper design is used to develop a new concept not based on a parent design but developed based on broad and challenging set of the client's requirements (Keane & Tibbits, 2013). In general, such projects are considered time consuming and prone to large iterations that influence the ship design, business case development and system design (ibid.). Several researches aimed to develop design strategies starting from a blank sheet of paper: recent developments explored the influence of requirements (Andrews, 2004), functions, (Wolff, 2000), industries (Erikstad & Levander, 2012) or goals (Singer, et al., 2009), but none appear to provide the support for a generic project seen in practice, which may lead to the many solutions seen abroad. Furthermore, only a limited number of these theories are applied in practice, in particular in commercial ship design.

Brett & Ulstein (2012) identify that there are some guidelines available in literature related to the role of creativity in ship design, in particular in creative ship design (Andrews, 1981), requirement elucidation (Andrews, 2004) and innovation in ship design (McKesson, 2013). The work of Andrews discuss the creative development of the ship design with respect to the business case. Innovation in ship design is discussed in a recent PhD research by McKesson concentrating on the generation of innovative ideas ('inventing'), reviewing innovation theory and tools to develop an innovation morphology, supporting the generation of innovative solutions (McKesson, 2013). McKesson's research identifies a common architecture in innovation algorithms based on creative approaches as for example Brainstorming, Synectics, Quintillian, Martin Gardner, Multitasking, Visual analysis, Biomimetic, MUDA and TRIZ. The thesis explores questions such as what is innovation, how do innovators think and can it be taught? The research does not review how ship designers develop innovative solutions in practice, but it creates an architecture based on a theoretical review complemented with the researcher's experiences. This architecture is tested in student projects or reviewed from projects in retrospect, exploring the creative 'invention step'. This review of the invention literature provides insight but it does not answer how innovations are developed in practice, as it concentrates on only a single element in innovation: the invention step.

Except for the three publications mentioned above, the majority of ship design theories do not discuss the creative elements of product development (Brett & Ulstein, 2012), and none of the theories describe how the different processes result in the different, innovative vessels seen in practice: hence the focus of this study. To explore the subject of innovation in ship design further, the process of innovation has to be further defined (1.3) and some initial steps should be taken to recognize innovative solutions (1.4).

1.3 Researching the process of innovation

The literature discussing innovation is extensive: there are designated academic journals, but innovation is also part of other fields of research including product development, architecture, civil engineering and aerospace engineering. Within innovation, creativity plays an important role, this role is discussed first (1.3.1), before exploring the innovation literature (1.3.2) and engineering design processes (1.3.3) as a source for innovation.

1.3.1 The role of creativity

Creativity: or the use of imagination or original ideas to create something (Oxford University Press, 2015), plays an important role during the development of innovative, large and complex vessels. Dependent on the set of literature, creativity contains the development of new products, which also includes art and science (McKesson, 2013). Other researches identify creativity as an essential part of innovating, defining innovating as implementing original ideas in an existing context (Amabile, 1996; Howard, et al., 2008). This research follows the latter definition, in which creativity is a used part in the innovation process, this in contrast to the work of McKesson, who sees the development of new products as a part of creativity.

The processes of developing ideas and implementing creative ideas resulting in innovative solutions are often called innovation processes or innovating (Smulders, 2014). These innovation processes closely resemble what in the maritime industry is often called the ship design process, although innovation processes in general allow for more creativity (Chapman, 2006). To keep the terminology consistent with the ship design literature, this research focusses on the design process of large, complex vessels, with a particular interest in approaches that allow for more creativity.

1.3.2 Innovation as a field of research

With creativity identified as an important activity in developing innovations, the question remains if the innovation literature would provide a process how to develop innovative, large and complex vessels. The innovation literature in itself is extremely broad. Literature evaluating innovation from an economic perspective (Schumpeter, 1942), evaluating dispersion of innovation and continuous innovation as part of the economic chain are all part of this field of research. Other literature evaluates the social consequences of innovations (Filchy, 2007) or reviews innovation from a business perspective (Utterback & Abernathy, 1975), to name just a few.

The most promising field for this research is the evaluation of innovation from a technology perspective. The majority of publications within this field concentrate on fast-moving consumer goods, objects that are built in large volumes based on a single design, resulting in theories for example concentrating on the fuzzy front end of innovation (Koen, et al., 2001) or the interaction between design and production (Smulders, 2006). These fields provide interesting insights, but do not provide direct answers for the ship design industry.

1.3.3 Engineering design processes as a source of innovation

Innovation processes in this research are defined as design processes that allow for more creativity (Chapman, 2006). The initial exploration of the innovation literature illustrates that it does not provide a direct answer for the challenges found in this research. The engineering design literature could provide other potential solutions. This field includes a wide range of design and engineering processes available, ranging from basic approaches (Jones, 1962; Darke, 1979; March, 1984; French, 1999) to detailed product development approaches (Pahl & Beitz, 1984; Hubka & Eder, 1988; Jänsch & Birkhofer, 2006).

These processes are valuable in providing a framework for the concept and engineering phases of the product development process. However, engineering design processes are poor with regards to reflecting creative processes (Howard, et al., 2008) and therefore do not reflect the innovation processes or creative (ship) design processes this research seeks to explore. This is illustrated further by Andreasen & Howard, who discuss the disappearance of engineering design from design research (Andreasen & Howard, 2011), potentially identifying a similar gap in the ship design literature.

Following this brief review, the ship design literature, the innovation literature and the engineering design literature do not provide a direct answer to describe how a broad spectrum of innovative vessels is developed by experienced ship designers; even though in practice, this is occurring regularly.

1.4 Identifying creativity and innovating

There is limited knowledge about the influence of creativity and innovation on the development of large, complex and innovative ship design as indicated above. This review raises subsequent questions: how do we recognize creativity and innovation within ship design projects? And following these questions, how to describe the process of developing innovative solutions, or 'innovating' (Smulders, 2014), (figure 1-5). This is a process that includes both creative activities and the implementation of the resulting creative ideas (Amabile, 1996) in the vessel. To identify both activities the creative activities (1.4.1) and the innovative content (1.4.2) are discussed in more detail.

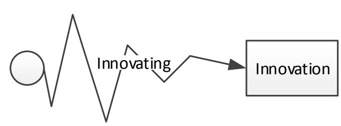


Figure 1-5. The difference between the verb and the noun (based on (Smulders, 2014))

1.4.1 Recognizing creativity

Creativity is defined as one of the key elements of new product development, but still only a small amount of theoretical frameworks are able to illustrate creativity. CK theory was introduced in 2002 with the aim to provide a rigorous, unified and formal network for design which includes all different forms of creativity. The theory is based on the assumption that design is modelled as the interplay between two independent spaces, each with their own structure and logic: the Concept (C) space and the Knowledge (K) space (Hatchuel & Weil, 2002).

The knowledge space contains all propositions with a logical status: representing a collection of available knowledge with a high degree of certainty. The concept space contains all undecidable propositions: propositions related to objects whose existence is not necessarily true or untrue in the knowledge space, with considerable uncertainty. CK theory could help to recognize creative designs as these designs include elements that, at some stage in the development, were conceptual (Hatchuel & Weil, 2009), and thus in the C-space.

1.4.2 Characterizing innovative designs

Comparing different projects in the ship design industry is very difficult, as each vessel is modified or developed for a designated client and are therefore distinctly different. Luckily, several theories provide guidelines to characterize and compare these different vessels, an important part if innovative designs are reviewed in a later stage.

The first guideline is provided by the most generic classification in the innovation literature, based on the extents of the innovation spectrum. Minor innovations are described as evolutionary, incremental or sustaining. Major innovations are described as revolutionary, radical and disruptive (Garcia & Calantone, 2002). Henderson & Clark describe that within the majority of innovation literature a categorisation between two elements is deemed unacceptable (Henderson & Clark, 1990), but developing a generic and acceptable measure for innovative content proved to be complex (Romijn & Albaladejo, 2002; Martínez-Román & Romero, 2013). A myriad of researchers have been developing their own structures, ranging from frameworks based on core concepts and their interactions (Henderson & Clark, 1990), to structures based on a literature review of innovation topology and innovativeness terminology (Garcia & Calantone, 2002) or a meta-typology to determine novelty (Chandy & Tellis, 2000). Ship design research developed their own structures, defining variant, adaptive and original design (Mistree, et al., 1990), or a range of ship design types (Andrews, 1998), (table 1-1).

Table 1-1. Types of ship design: left, (Andrews, 1998), right (Mistree, et al., 1990)

Type
Second batch
Simple type ship
Evolutionary design
Simple synthesis
Architectural synthesis
Radical configuration
Radical technology

Type
Variant design
Adaptive design
Original design

As this research explores how ship designers develop different innovative solutions it is not necessary at this stage to select, refine or rephrase a typology to describe innovative content; it is sufficient to acknowledge innovative content as a range between incremental and radical innovation (figure 1-6).

Figure 1-6. Innovative content as a range between incremental and radical

Ship design theory in general identifies that the innovative content of a vessel has a considerable impact on the development. For example the design spiral which is suitable for incremental, second batch or variant designs (Evans, 1959). Or original and radical designs, which require a different design strategy (Mistree, et al., 1990). Mistree and his co-authors conclude that the major issues facing the ship designer are different depending on the type of design (ibid.), yet, they do not illustrate what these challenges are. The ship design literature recognizes the influence of innovative content, none of the available theories provide a concluding framework describing the effect of different innovative content on the design strategy.

1.5 Focus of inquiry

Based on the observations documented in this chapter an initial problem definition (1.5.1) and research objectives (1.5.2) are defined, leading to the initial research question (1.5.3).

1.5.1 Defining the initial situation

Innovative, large and complex vessels are developed specifically for a designated client, based on their objectives, requirements and preferences. In general, ship designers are able to develop a broad range of innovative solutions to solve a broad range of challenges posed by their clients. Still, how such different solutions are developed is not clear and seems to be dependent on the experience of the ship designers and the situation they are in. This lack of understanding makes the industry very dependent on these ship designers, making it difficult to improve the ship design process for such vessels and to teach ship design to young, aspiring ship designers.

To increase understanding of how the design process of developing large and complex vessels occurs, this research needs to:

- Explore the approach experienced ship designers apply within projects, to create a better understanding of the activities in ship design practice.
- Identify and model the key features of the approach of experienced ship designers in developing innovative solutions and evaluate if the model has value for practice.

1.5.2 Research objectives

The objectives of this research are twofold:

- From an academic point of view, researching innovative ship design practice aims to add to the body of knowledge, related to the innovative content of ships and the effect is has on the ship design process, creating a basis to develop tools and techniques. If this objective can be achieved, the knowledge base can support young ship designers in developing successful innovative solutions.
- From a practical point of view, researching innovative ship design aims to support the design process of innovative, large and complex vessels by applying design strategies better suited to the client's requests.

1.5.3 Research question

Both the problem definition and the research objective illustrate the targets of exploring the challenges related to creative design process within the ship design practice. The initial research question is therefore extensive:

How are innovative, large and complex vessels developed in practice?

The broad nature of this initial research question cannot be explored with a research strategy aimed on validation and verification, but requires a more explorative research method. Based on the results of this exploration the parameters can be defined and a working hypothesis can be constructed to test the observations in practice (chapter 5). The selection of this research strategy is discussed in more detail in chapter 2.

Chapter 2

The researcher/practitioner

"Defining a research approach
to explore the initial challenges"

The ship design industry is capable of developing very different, innovative ship designs, despite the fact that the theoretical background of ship design does not appear to describe how innovative designs are developed (chapter 1). This research is initiated in order to create a better understanding of how the different actors such as ship designers develop creative and innovative ship designs. The practice-oriented nature of the subject drives the researcher into the world of active, innovating naval architects and designers. This causes considerable methodological issues: how does a researcher objectively explore the design of a complex object, even though (s)he is an integral part of the environment in which these developments occur?

This explorative research aims to enrich the theoretical background related to creative and innovative ship designing based on observations in practice. The main focus of the research is on discovery, augmenting existing or developing new theory based on the practitioner's activities. Starting a research which aims for discovery results in a different set of challenges for the researcher compared to a research aimed at validation and verification of existing theory. Such challenges require additional attention with respect to the research design. Based on the challenges (2.1) a strategy suitable for this research is selected (2.2). Section 2.3 expands the research strategy to develop a research design suited for the problem at hand (figure 2-1).

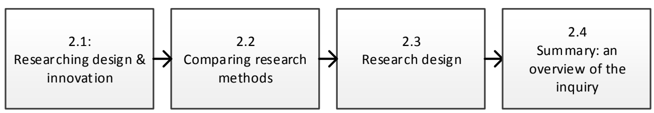


Figure 2-1. An overview of chapter 2

2.1 Researching design & innovation

The explorative nature of this research does not suit the rationalistic and deterministic research design that aims for justification instead of discovery (Popper, 1959); the current dominant scientific approach in maritime technology (Zwart, 2011). The aim of developing new and enriching available theory based on practice does cause several research challenges, challenges that have to be resolved in the research design. In his research on the role of designers in multidisciplinary teams Stompff summarizes two main challenges related to conducting research in practice: the researcher as part of the environment (s)he is researching and the tacit dimension of knowledge related to the research subject (Stompff, 2012).

1. **The researcher as part of the environment (s)he researches:** This research aims to enrich the available theory based on the activities of naval architects or ship designers in practice. Enriching theory based on the ship design practice causes considerable issues as it tries to capture knowledge that is embedded in the practice of the involved actors or, as Stompff defines it; "knowledge of which they themselves are unaware" (Stompff, 2012). To access this particular knowledge Stompff identifies that the researcher cannot be an external observer, but needs to become a participator to gain insight and conduct experiments in practice (ibid.). This means the researcher has to rely on practice, which consists of many actors that interact in a large variety of ways dependent on the respective relationships between them. Such a situation is not always at ease with the research agenda;

one example is that the researcher does not have control if and how experiments (testing the observations) are conducted. Furthermore, because of commercial and practical limitations the access and availability of data may be limited, especially if experiments are conducted in collaboration with other companies in the industry. The challenge is to find a research approach that allows for interaction between both the researcher and practice mitigating the related challenges.

2. **The tacit dimension of knowledge:** Erikstad characterizes ship design as heavily dependent on experience of the involved naval architects: it is based on a shallow knowledge structure derived from the use of previously built ships (an extensive, implicit understanding of ship design) and has a strong domain tradition, relying on the design practice of the experienced naval architect (Erikstad, 1996). In academic literature this experience is defined as the tacit dimension of knowledge (Nonaka, 1991), either defined as 'practice-based' (Polanyi, 1966) or 'know-how' (Ryle, 1949). The dependence of practice on the tacit dimension of knowledge makes it very difficult to discuss and evaluate data articulated by the involved actors. To facilitate exploratory research within this practice, it is necessary to find a research strategy that attunes the required tacit knowledge between the researcher and the practitioners.

Both challenges can be solved by selecting the correct research approach which allows for interaction between practice and theory and supports the continuous attenuation of knowledge between the involved actors and the researcher.

2.2 Comparing research methods

Three approaches potentially applicable to this research are explored and compared to select the most applicable approach based on the challenges discussed in the previous section (2.2.1). The subsequent section discusses the related methodological issues (2.2.2).

2.2.1 Exploring potential research methods

Ethnography (Plowman, 2003), Action research (Swann, 2002), Grounded theory (Glaser & Strauss, 1967), and the Deweyan inquiry (Stompff, 2012) are identified as potential research methods that support practitioners who want to add to the theoretical basis of their field. Ethnography concentrates on the systematic study of human cultures, an effort which does not appear beneficial for this particular research. The other three methods are closely related, but do have some key differences (Stompff, 2012). Action research and the Deweyan inquiry share the same theoretical base laid down by Dewey, both in the philosophical work and the experiments in education (Brydon-Miller, et al., 2003; Stompff, 2012). Grounded theory finds its theoretical basis in the social sciences, but is, similar to Action research and the Deweyan inquiry, aimed at the development of new theory (Glaser & Strauss, 1967; Smulders, 2006). Grounded theory, Action research and the Deweyan inquiry are discussed here and visualized in figure 2-2.

Grounded theory (figure 2-2, right) has the objective to generate theory, which accounts for a pattern of behaviour which is both relevant and problematic. The research approach is based on collecting and analysing data and subsequently develops an initial draft of theory. This initial draft of the theory provides input for another more focussed data collection from practice, the analysis and improving the derived theory (Glaser & Strauss, 1967; Glaser, 1992; Smulders, 2006). Grounded theory identifies multiple stages of maturing within an iterative process, where a theory matures from an initial draft to a generalizable theory, continuously attenuating knowledge. Grounded theory does provide a disconnected perspective on the interaction between the researcher and practice and therefore does not bring much opportunity for creating insight in the tacit knowledge of the designer. Practice is observed and used as a basis for the development of theory, but there is no mutual interaction between the researcher and involved actors.

Action research (figure 2-2, middle) is a practical research methodology aiming to change an existing practice using existing theory. The process goes through a spiral of cycles which include the 4 steps in action research: Plan – Act – Observe – Reflect (Swann, 2002). The approach has been further developed into reflective action research, which puts more focus on the theoretical development through doubt of the original theory, developing these doubts, modifying theory and the decision to apply the modified theory (Boonstra, 2004). In both action research and reflective action research, the researcher actively provides input and supports the planning phase as practice and research interact. Dependent on the situation the researcher can be either participatory or take the role of external researcher, modifying existing theory and develop hypotheses. In the first approach, the action researcher actively takes part in the change, in the latter practitioners implement the hypothesis as changes, a situation where the practitioner's actions serve as experiments. Action research aims to modify existing practice with the support of (modified) theory. The involved researcher may use the changed practice to validate and extend theories through observing the results of the practitioner's activities, initiated by the researcher (Brydon-Miller, et al., 2003).

The **Deweyan inquiry** (figure 2-2, left) is a relative new development of a research strategy, specifically developed to support 'practitioners doing research' (Stompff, 2012). It is based on the writings of the North American pragmatists, where philosophers such as Dewey, Mead and Pierce developed a research method called the 'pragmatic inquiry', an approach based on the philosophy that humans interact with the world, and can therefore not be seen as inert observers (Stompff, 2012). The pragmatic inquiry is an influential method in science, but is primarily developed in the fields of education (Schön, 1992). Guido Stompff in a relative recent development applied the pragmatic principles (in particular the principle that humans are not inert observers, but part of the world with an active role in it) found in the original writings by Dewey (Dewey, 1938) to develop a research strategy aimed to support the researcher/practitioner in an environment exploring design, (Stompff, 2012). The Deweyan inquiry aims on discovery, incorporating the development of theory by a synergy between the domains of practice and theory by supporting the researcher/practitioner. The inquiry complements the development of the original doubt with testing of theory by modifying practice (similar to action research). The Deweyan inquiry incorporates a broader research scope or the full pragmatist circle in comparison with both Action research and Grounded theory, supporting the practitioner doing research; not only developing, but also implementing theory within practice (Stompff, 2012).

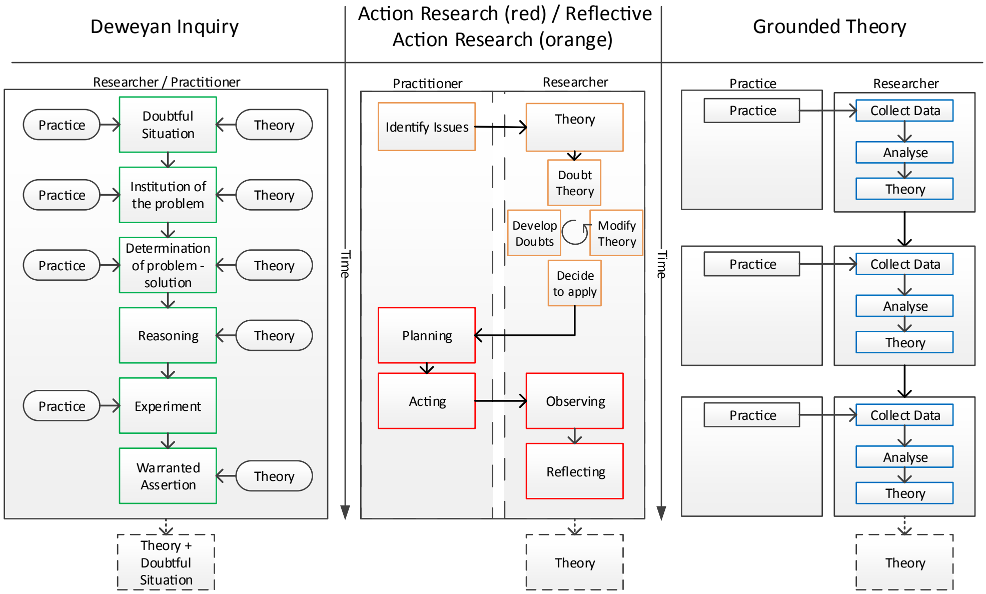


Figure 2-2. Representations of the Deweyan inquiry (Stompff, 2012), Action research (Swann, 2002), Reflective Action research (Boonstra, 2004) and Grounded theory (Glaser & Strauss, 1967)

Grounded theory requires a separation between the practitioner(s) and the researcher, a situation which is difficult to realize when the research is conducted in ship design practice as discussed in section 2.1, (1). Both grounded theory and the Deweyan inquiry allow for the continuous attenuation of knowledge of the researcher, as discussed in section 2.1, (2), grounded theory develops this by observation. The Deweyan inquiry allows for an interactive combination of practice and theory, supporting the role of the researcher/ practitioner. The Deweyan inquiry and Action research are closely related, both are based on a pragmatist view and take planned action in practice. The Deweyan inquiry appears to provide a more extensive guideline as it is not only based on taking action, but also develops doubts based on practice and theory; the full pragmatist circle.

For this research, the Deweyan Inquiry appears to be the most suitable research methodology. This research methodology is used to explore how innovative solutions are developed within ship design, mitigating the methodological issues described in section 2.1. The application of the Deweyan inquiry does result in some inherent challenges which have to be covered by the research design for this specific research. These challenges are discussed in the subsequent subsection.

2.2.2 Challenges in applying the Deweyan inquiry

Using the Deweyan inquiry as a method has both advantages (discussed in subsection 2.2.1) but also some challenges. An extensive review of such challenges is discussed in the work of Stompff (Stompff, 2012). The two challenges relevant to this research are summarized below: The first discusses the biases involved with the position of the researcher/practitioner. The second discusses the interplay between the researcher and the research subject and the consequences on the research.

1. **Engagement bias:** Being directly involved within the research subject is not only beneficial, it also causes a challenging situation. The majority of these issues are directly related to the perspective of the researcher: the risk of both individual and professional bias. Individual bias, sometimes found in social sciences, occurs when researchers ignore instances that falsify their own hypothesis (Judd, et al., 1991). Professional biases occur in practice, where practitioners have a 'blindness for their own practice' (Stompff, 2012). To mitigate this, the researcher/practitioner needs to enhance his observational skills and special attention has to be given to research tools that support engagement, but reduce the occurrence of both professional and individual bias by increasing triangulation and trustworthiness.

2. **Intervention / reflexivity:** Intervention and reflexivity are closely related: intervention is the deliberate influence of the researcher on an ongoing project to improve the changing state. Reflexivity is the unintended influence of the researcher on these ongoing projects, because of his presence and activities (Nightingale & Cromby, 1999). Both intervention and reflexivity require reflection and exploration of the way this influence occurs (ibid.). The Deweyan inquiry actively uses intervention, supporting the research/practitioner in modifying practice and developing theory. As a consequence, reflexivity always occurs but the consequences have to be documented and evaluated as part of the approach.

Both challenges discussed in this section should be taken into account when developing the Deweyan inquiry into a research approach for this specific research. The design of a more specific research approach, aiming to mitigate these challenges is developed further in section 2.3.

2.3 Research design

As described in section 2.2, the Deweyan inquiry is a research method which aims to develop new theory in close interaction with the current state of practice. The research approach, with its close interaction between theory and practice does result in challenges as discussed before, which should be taken into account while developing the generic framework into a research specific approach. In this section, the framework based of the Deweyan inquiry is discussed in more detail. The main challenge in the research based is to reduce the impact of engagement bias and reflexivity, this can be reduced by improving the research rigor, for example by borrowing from rationalistic research techniques when collecting and evaluating data.

2.3.1 The structure of the research design

According to Dewey, *"inquiry is the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole"* (Dewey, 1938, p. 108). In brief, it transforms an initial doubtful situation into a unified whole through a guided approach. The Deweyan Inquiry according to Stompff consists of six steps, shown in figure 2-3 (Stompff, 2012).

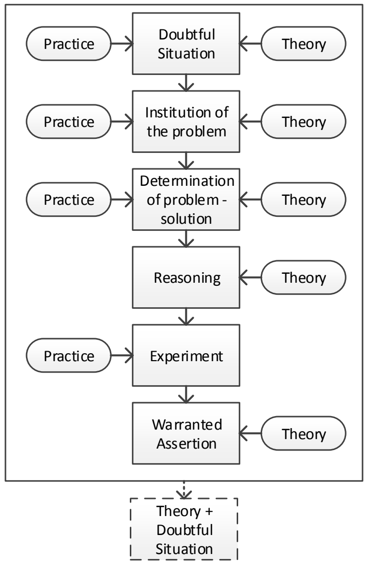


Figure 2-3. The Deweyan inquiry (Stompff, 2012)

Each step is developed based on a frame of reference provided by the previous phase. The Deweyan inquiry takes a Darwinian approach to theory development (Stompff, 2012): only developing theory further which has actual value in practice. Each subsequent step sharpens and improves the available frame of reference, continuously improving the theory under development. The final set of theory is therefore developed through several iterative steps influenced by both theory and practice, and testing using interventions in practice, akin to action research. The six steps of the Deweyan inquiry are discussed in more detail:

1. **Doubtful situation:** A Deweyan inquiry starts with a situation that is problematic, confusing, uncertain or conflicted. Often the doubtful situation is found by practitioners in practice. The situation triggers the practitioner to decide that this particular situation requires further inquiry, supported by input from both theory and practice. In this research, the doubtful situation is sketched in chapter 1, which provided the starting point for this research.

2. **Institution of the problem:** During the institution of the problem the doubtful situation is provisionally pinpointed, judged and framed by the practitioner. This framing is based on both theory and practice: observations are required to define the problem, however, to make these observations explicit a theoretical basis is required. There is a clear duality of theory and practice, as both complement each other to define and frame the initial doubtful situation. The Deweyan inquiry does not prescribe how to conduct observations in practice, although this has considerable impact on the engagement bias of the researcher. How these observations are approached is discussed in subsection 2.3.2.

3. **Determination of problem – solution:** The third step defines hypotheses describing both the problem but also potential solutions. The coexistence and co-emergence

of problems and solutions is an important part of the Deweyan inquiry, as it reconstructs the previous situation, determining leading factors and their relations, but also identifies solutions to solve the initial problems. The problem-solution is developed based on and supported with influences of both practice and theory, developing problem solutions that are both relevant, flexible, usable and suitable.

4. **Reasoning:** The subsequent phase develops the problem-solution identified in step 3, evaluating the consequences of the potential solution on the current situation. The step generates productive 'if-then' statements, which provide a starting point for the subsequent experiments to be conducted in practice: the working hypothesis. This step is primarily supported by theory, as it aims to predict the consequences of a certain solution on the current situation.

5. **Experiment:** The working hypothesis developed in the previous steps is put to the test in practice. These interventions aim to solve the initial doubtful situation, changing a practical situation to mitigate the initial problems. The changes to the original situation are used to develop the concepts and ideas by observing and reflecting on the results of the researcher/practitioners actions. The Deweyan inquiry identifies that the experiments intervene in practice, testing the solutions developed in the previous step, yet it does not describe how they should be conducted, similar to step 2. The approach used to conduct these experiments has considerable impact on evaluating the reflexivity the researcher has on the subject. How this particular challenge is approached is discussed in subsection 2.3.2

6. **Warranted Assertion:** The inquiry is a progressive and cumulative approach: changes have been made to the original situation and the situation is rearranged and developed. The final step is therefore to evaluate the changes applied to the original situation and determine if the situation developed positively for the involved actors. Furthermore, as it is cumulative, the warranted assertion includes an analysis of challenges in the new situation (or new doubtful situations) as a starting point of further research cycles.

The warranted assertion results in both new theory and a (new) doubtful situation, which may provide a starting point for further research. The structure of this research supports the position of the researcher /practitioner and allows for close interplay between theory and practice while developing and discovering new theoretical frameworks.

2.3.2 Reducing engagement bias and impact of reflexivity

The Deweyan inquiry aims at discovery of theory but not the scientific validation thereof. The strong practice-based foundation of the overall research structure makes sure that the research is expected to have sufficient relevance to the overall field. This is complemented by the experiments or interventions which aim to verify the developed theory in practice. Still, Stompff found during his research using this approach that the research subject "design in the wild" is by its nature at unease with scientific research rigor, necessary to ensure validity and reliability (Stompff, 2012) and to reduce the impact of engagement biases and reflexivity (as discussed in subsection 2.2.2).

The structure of the Deweyan inquiry (figure 2-3) already aims to increase the scientific rigor by applying a sequential approach: observations from practice are used to derive and improve the theoretical frameworks. Subsequent tests apply these theoretical frameworks to explain previous observations and verify if the theory suits current practice. This alternating, sequential nature, in which theory is used to prepare a framework for observations in practice, while the observations from practice are used to derive a new and improved framework to explain previous observations is shown in figure 2-4.

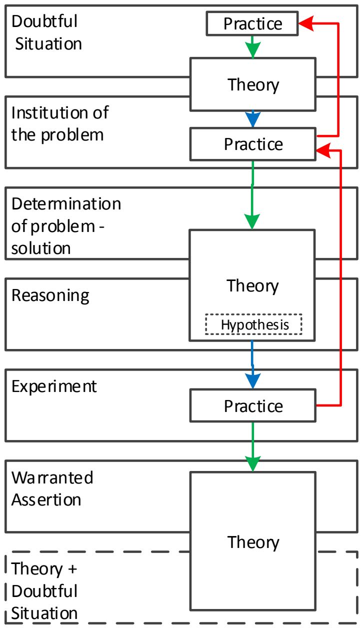


Figure 2-4. The sequential nature of the research design: theory is derived from practice (green), theory used to prepare for practice (blue). Interventions in practice are used to explain the original situation (red)

There are two key steps where the interaction with practice has considerable influence. During the institution of the problem and the experiments (figure 2-3) observations in practice are used to derive theory and to explain previous observations. Such a close interaction with practice, increases the relevancy of this research, yet it does require attention with respect to research rigor, to enable structured observations. This is further discussed in subsection 2.3.3.

2.3.3 Research tools for observing practice

During the institution of the problem the observations in practice aim to explore how creative and innovative designs are developed. During the experiment an intervention in practice results in a new set of observations describes the consequences of the changes prepared during the reasoning (step 4 in the Deweyan inquiry, 2.3.1). The exploratory and descriptive nature of the individual steps serve the Deweyan inquiry by resolving the doubtful situation.

To increase rigor the research tools applied in both the institution of the problem and the experiments have to be carefully selected. There are different tools available for such steps, including controlled experiments, surveys, archival analysis, historic analysis and case studies. Table 2-1 shows the relevant situations in which to apply these research tools, based on the form of the research question, the control over behavioural events and the focus on contemporary events.

Table 2-1. Relevant situations for different research strategies (Yin, 1994)

Tool	Form of research question	Requires control over behavioral events	Focuss on contemporary events
Experiment	How, Why	Yes	Yes
Survey	Who, What, Where, How Many, How Much	No	Yes
Archival analysis	Who, What, Where, How Many, How Much	No	Yes/No
History	How, Why	No	No
Case study	**How, Why**	**No**	**Yes**

In both the second and fifth step of the Deweyan inquiry case studies appear to be the relevant research tool: The research concentrates on how creative and innovative designs are made, the researcher has limited control over behavioural events and both the institution of the problem and the experiments concentrate on contemporary events. The research protocol used in each individual case study is based on the work of Yin (Yin, 1994). The protocol is visualized in figure 2-5, with a step-by-step review provided in the subsequent paragraphs.

Figure 2-5. Case study procedure (Yin, 1994)

1. **Framework:** Within the research structure, defined by the Deweyan inquiry, the framework for each set of case studies is based on the theoretical framework developed in the previous research step. The theoretical framework for the case studies is provided in subsection 4.1.2 and 7.1.3.

2. **Case selection:** The initial framework from the previous step provides a basis to select the case studies. The selection of the cases studies is provided in subsection 4.1.4 and 7.1.4.

3. **Data collection:** One of the advantages of researching real-life projects is the potential access to a wide range of data. Case studies within this research are based on available documentation, interviews, archival records, publications, patents, direct observations, related academic research and physical artefacts. In some cases, access to certain types of data could be limited because of commercial interests, therefore each individual case study discusses the available dataset in more detail.

4. **Case reporting:** Each case study is developed into an individual case study report. Each report is reviewed by the involved parties to ensure an unbiased description of the developments. These reports are commercial in confidence and not included in this book, please contact the author for more information. The case studies are summarized in chapter 4, section 5.3.3 and chapter 7.

5. **Cross-case conclusions:** Based on each set of case studies, cross-case conclusions are developed. In this dissertation, the cross-case conclusions are found in section 4.6, chapter 5, section 7.4 and chapter 8.

The case study protocol is applied in both the institution of the problem, where practice is explored to pinpoint the initial doubtful situation (chapter 4) and during the experiments, describing the effects of the changes (chapter 7).

2.4 Summary: an overview of the inquiry

The selected research approach aims to explore how creative and innovative ship designs are developed in practice. The research design is based on the Deweyan inquiry, a research method which supports the position of the researcher/ practitioner, the dual development of both theory and practice and allows interventions of the researcher in practice. To mitigate the inherent methodological issues of the method and especially the engagement biases that could occur case study research is applied: a tool with a rationalistic background.

The explorative nature of this research makes it more challenging to evaluate the end result, as it aims to develop new theory compared to a rationalistic and deterministic research project aimed at justification of existing theory. The often used tools of validation and verification in rationalistic and deterministic research are unsuitable for this explorative research. The evaluation applied in Grounded theory research: fit, relevance, workability and flexibility (Glaser & Strauss, 1967), (Glaser, 1992) is more suited to evaluate the results of research with an explorative nature, evaluating the value of the newly developed theory for both practice and theory.

This evaluation is conducted in chapter 8 to determine if the newly developed theory provides insight in the initial doubtful situation and if the theory is applicable and sufficiently generic for the practice it is describing. The structure of the dissertation correlates with the research design developed in this chapter. The overall structure of the dissertation is visualized in figure 2-6.

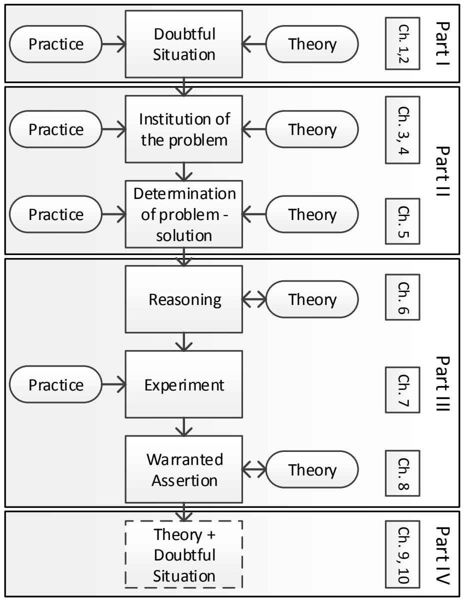


Figure 2-6. The overview of the inquiry

The first part of this dissertation ("The doubtful situation") includes chapter 1 and 2. The first chapter, the introduction, discusses the initial doubtful situation, the starting point of this research based on both practice and theory. The current chapter, chapter 2, discusses the research approach based on the Deweyan inquiry applied within this thesis.

Part II ("Describing ship design") aims to describe the current state-of-the-art in ship design, both in practice and literature. Both chapter 3 and 4 support the institution of the problem: chapter 3 reviews the state-of-the-art literature on ship designing, chapter 4 explores practice using four different case studies. The observations in both practice and theory are combined in chapter 5 to determine the problem-solution, proposing a new perspective on the design of innovative and creative ships.

Part III ("Controlling ship design") tests if the observations made in part II improve control over the development of creative and innovative ship designs. Chapter 6 expands the current theoretical framework to predict the consequences of the observations of chapter 5. The framework developed in chapter 6 is tested in two commercial project, discussed in chapter 7. The final chapter of this part reviews the results of these two experiments and compares them to a reference case, drawing cross-case conclusions.

The final part of this thesis ("Conclusions and Recommendations") discusses the results of this thesis. Chapter 9 explores a new doubtful situation, which is related to the social dimension of the ship design practice. Chapter 10 concludes this dissertation by discussing the fit, relevance, workability and flexibility of the developed theory and evaluating the current situation in practice.

Part II

Describing ship design

Chapter 3

Designing complex, innovative ships: state-of-the-art

"Exploring the available ship design literature"

This is not the first research aimed at describing ship design, therefore this chapter discusses the most influential and relevant ship design methodologies and tools. It provides a theoretical framework supporting the institution of the problem in the Deweyan inquiry (figure 3-1).

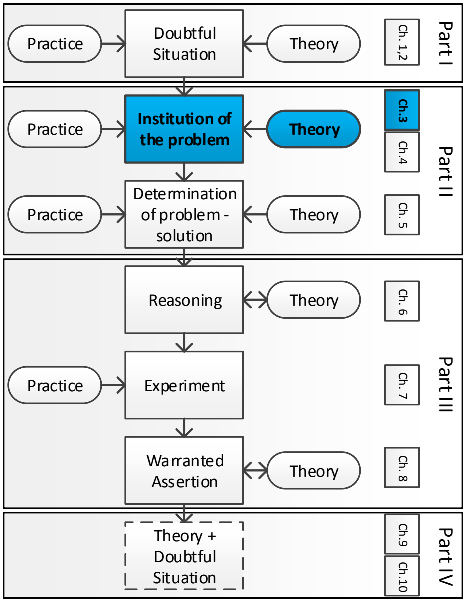


Figure 3-1. Overview of the research stages (equivalent to figure 2-6)

Ship design methodologies and tools are evaluated to determine if and how they allow for various creative and innovative solutions seen in practice. Furthermore, the discussed theories provide input for the framework that supports the evaluation of current practice in ship design discussed in chapter 4. Each subsection explores the origins and the current applications of a methodology, method or tool. The selection of the theories and the lens required to evaluate the creative and innovative elements of these theories is described in 3.1. The chapter explores generic ship design approaches (3.2), system thinking based approaches (3.3) and tools supporting creative ship design (3.4) before drawing conclusions in section 3.5 (figure 3-2).

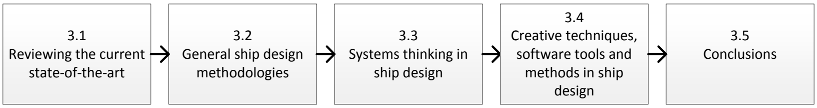


Figure 3-2. An overview of chapter 3

3.1 Reviewing the current state-of-the-art

Ship design literature is very broad and covers a wide range of subjects ranging from design strategy and software tools to hydrodynamics and machinery. For the purposes of this research a full review of literature related to ship design would be irrelevant as this thesis concentrates solely on the first stages of developing innovative vessels. To limit the scope of this review the selection of applicable publications is discussed in subsection 3.1.1, before the initial framework or 'lens' is built to evaluate these theories in subsection 3.1.2.

3.1.1 Identifying the current state-of-the-art

The selection of literature discussed in this chapter is based on the state-of-art reports presented during the triennial International Marine Design Conference (IMDC), (Andrews, et al., 2006; 2009; Papanikalauo, et al., 2012; Andrews & Erikstad, 2015). These state-of-art reports are complemented by other publications that provide an overview of ship design, such as the work of Mistree, Andrews and Brett & Ulstein (Mistree, et al., 1990; Andrews, 2012; Brett & Ulstein, 2012). Based on these publications the ship design processes are selected and divided into two groups: the general ship design methods, focussing on the ship design as a single object (3.2). Complemented with more system thinking based approaches, who manage the complex tasks by implementing hierarchy in the ship design process (3.3). These two groups show a shift in perspective: the first group belongs to the first cycle of design methods until the late 1980's, while the second group shows a system based approach where decomposition of the design problem is a key aspect. Such approaches became apparent in design research from the early 1990's (Andrews, 2012). The selected design processes and the two groups are visualized in simplified timeline in figure 3-3.

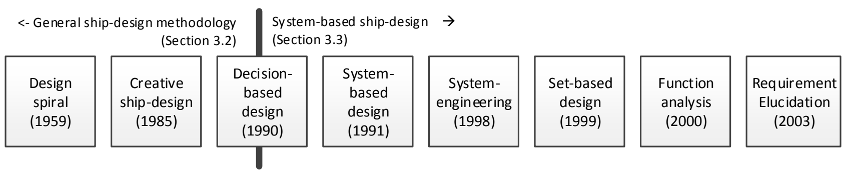


Figure 3-3. Simplified timeline of the development of ship design processes

Section 3.4 concentrates on more detailed descriptions of techniques, tools and methods applied within these respective ship design processes. There are many techniques, software tools and methods available in ship design, but to limit the scope of this part of the review only a limited selection is evaluated based on recent publications of tools that aim to support creative design. The selected tools, techniques and methods are visualized in a simplified timeline in figure 3-4.

Figure 3-4. Simplified timeline of creative ship design tools

3.1.2 Building a lens, defining an initial framework for analysis

This chapter aims to identify if available ship design methodologies and tools allow for creative and innovative solutions seen in practice. CK theory is applied to pinpoint and evaluate the creative aspects of the ship design methodologies. CK theory was introduced by Hatchuel & Weil in 2002 with the aim to provide a rigorous, unified and formal network for design which includes all forms of creativity (Hatchuel & Weil, 2002).

CK theory is based on the assumption that design can be modelled as the interplay between two independent spaces, each with their own structure and logic: the Concept (C) space and the Knowledge (K) space. The knowledge space is defined as containing all propositions which are either true or untrue, this space represents a collection of the available knowledge. The concept space is defined as the space containing all propositions related to objects whose existence is not necessarily true (or untrue) in the knowledge space. The elements in the knowledge space do not take into account any uncertainty. Conceptual elements do allow for uncertainty, as they can be either true or false. The relation within and between these two spaces is provided by five operators (Hatchuel & Weil, 2009), visualized in figure 3-5:

1, 2 Expansion in the concept space or in the knowledge space (C->C, K->K): expansion develops new information from existing concepts or knowledge into new knowledge and concepts. Examples of these operators include brainstorming, where a group of people respond to new concepts, or testing and generalizing scientific theories, expanding knowledge.

3. Conjunction (C->K): conjunction develops new knowledge based on a concept. For example the experimental testing of an innovative system or the production of a new ship design generates new knowledge about the concept.
4. Disjunction (K->C): disjunction defines new conceptual propositions; propositions that are not necessarily true but based on existing knowledge.
5. Partitioning (C->C1, C2): partitioning divides a concept into smaller sub-sets to test and evaluate the concepts in the design.

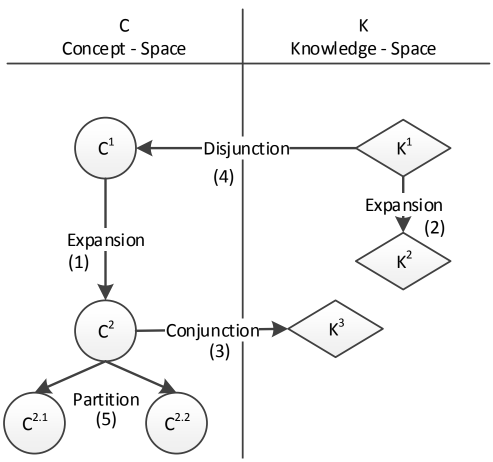


Figure 3-5. The visualisation of CK theory (based on (Hatchuel & Weil, 2009))

To allow for creative solutions to occur, a design strategy must allow for propositions within the concept space: propositions that at some point in the design process are undecided or conceptual, and can still be either true or untrue. To result in innovative solutions the approach has to develop these concepts (or 'undecidable') propositions into knowledge (or true/untrue propositions).

CK-theory is applied to determine if the ship design approaches discussed in this chapter allow for and are able to describe creative and innovative design; a process which should include disjunction, expansion, conjunction and possibly partitioning. Each subsection discusses the origins of the design process, identifies recent developments and evaluates if the process is capable and sufficiently generic to describe the process leading to the creative and innovative solutions seen in practice.

3.2 General ship design methodologies

General ship design methodologies describe the process based on the sequential development of a single, integral ship design which is modified until the requirements are met. Such approaches are often called 'point based' design approaches (Parsons, et al., 1999). The following methodologies are included:

- Design spiral (3.2.1)
- Creative ship design (3.2.2)
- Decision-based design (3.2.3)

3.2.1 Design spiral by Evans

The ship design spiral is arguably the most influential and most referenced design strategy within the ship design industry (Andrews, et al., 2012). The first mentioning within the academic literature related to ship design is from 1959, at this point the method was presented as a display of the rational, overall design procedure as applied to a hypothetical but typical, surface cargo ship problem (Evans, 1959), (figure 3-6). According to Evans, the approach starts with a rudimentary concept of the ship's general arrangement and an arbitrary but tentative choice of the type of main propulsion machinery. Based on these choices, a wide range of procedures is used to define principle dimensions and parameters. When all mutually dependent variables are in accord, a final refined and balanced design is achieved. The last cycle is therefore appropriately designated as the 'analysis' cycle, whereas the first cycles are the 'synthesising cycles', in which the interplay is essential to the final objective (Evans, 1959).

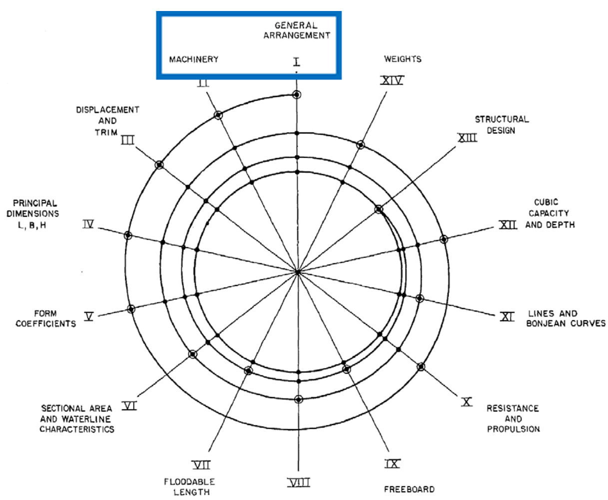


Figure 3-6. General design diagram (Evans, 1959) (equivalent to figure 1-5)

The ship design spiral is primarily used to describe the recurring activities and the increasing level of detail within the ship design industry (Hopman, 2008). The model was further developed in different papers, for example by adding economic considerations (Buxton, 1972), or adding another dimension showing the influence of direct and indirect constraints (Andrews, et al., 2009), (figure 3-7). Recent publications refer to the general design diagram as the Evans-Buxton-Andrews spiral (Mistree, et al., 1990; Gaspar, 2013). The work of Gale shows different baseline designs developed throughout the development applying the design spiral. The analysis and optimization of the elements in each baseline design are not developed sequentially but in parallel, applying concurrent engineering principles, based on the valid baseline design (Gale, 2003), (figure 3-8).

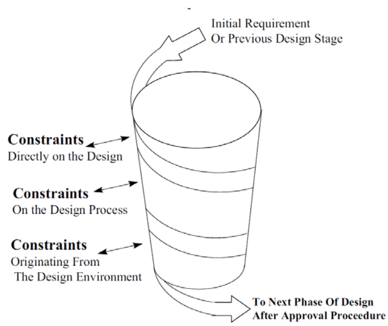


Figure 3-7. 3D design spiral (Andrews, 1981)

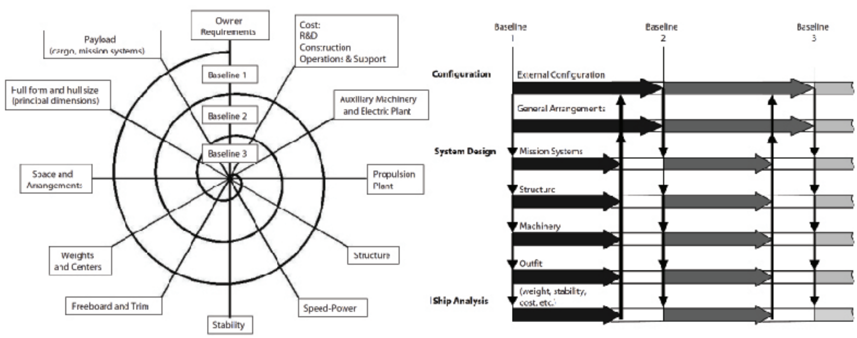


Figure 3-8. The design spiral and parallel developments (Gale, 2003)

The ship design spiral only allows for undecided propositions or ‘concepts’ in the initial phases of the spiral, when the rudimentary definition of the ship’s arrangement and choice of main propulsion machinery is developed (marked in blue in figure 3-6). Initial publications related to the design spiral illustrate that both the arrangement and main machinery have to be selected from existing solutions; solutions that are known and not conceptual. After these initial phases the approach concentrates on balancing and consolidating the layout and propulsion selection: The spiral type approaches described here handle undecided propositions as propositions that are true. If, during the project, these concepts prove to be untrue, major iterations are to be expected. Iterations that are not taken into account in the design spiral. The design spiral type approaches focus on the conjunction of minor conceptual changes into propositions that are either true or false (visualized in figure 3-9).

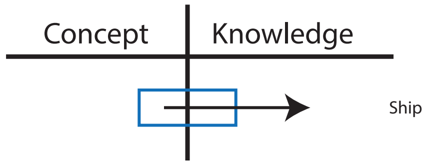


Figure 3-9. Visualization of the design spiral with respect to CK-theory, representing conjunction

Furthermore, the ship design spiral is not developed as a generic tool for describing innovative ship design, as Evans mentions: *"its precision suffers markedly if the extrapolation from prototype to new design is anything but very small. Worse still is the danger of unwittingly perpetuating redundancies and other faults of the parent design along with its virtues"* (Evans, 1959, p. 674). Evans specifically states that *"the exact use of the (Figure 1) model will not be ideal in all its aspects for design of extreme or unduly restricted character"* (Evans, 1959, p. 677). Or, as Rawson describes it: the design strategy is developed for minor modifications to a generic, large bulk carrier (Rawson, 2001).

3.2.2 Creative ship design by Andrews

The work of Andrews in the early 80's identifies the need to provide a design process which supports creativity in ship design. To support this creative approach two research paths are proposed. The first path concentrates on the synthesising of ship layouts with the support of CAD-systems. The second path discusses the overall approach to creative and radical design, concentrating on the synthesis of new ship designs by applying design philosophy, thereby letting the designer take control of the creative design process in designs with major modifications (Andrews, 1981), (figure 3-10).

The first path is further developed in later work, concentrating on the need for an integrated approach for ship design synthesis (Andrews, 1985), which is discussed further in this subsection. The latter path aims to pursue a more comprehensive design philosophy to deal with the design tasks of the future (Andrews, 1981).

The integrated model to ship synthesis includes both the initial sizing of the vessel as well as the initial ship synthesis using spatial tools and identifies the sequential nature by including feedback loops during key steps in the design. The approach recognizes the integrative behaviour of design: the evaluation of the layout cannot exist separately of the layout. The approach supports this by making choices of layout and evaluation tools more explicit. The concept of creative ship design and integrating the synthesis of the conceptual design in the early stages of the design concept is developed further into software tools (Pawling, 2007), (subsection 3.4.1) and a myriad of papers by David Andrews.

The synthesis model proposed by Andrews (figure 3-10) concentrates on the synthesis of the layout of the vessel (Andrews, 1985), it allows for undecided or conceptual propositions, but only in this layout during the synthesis of spatial disposition and ship gross size (marked in blue in figure 3-10). The steps before this synthesis step create the initial conditions for this conceptual development (disjunction), before developing the

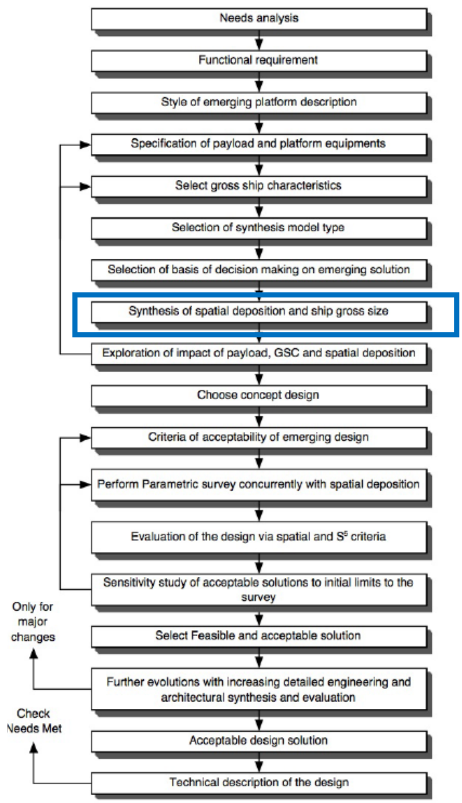


Figure 3-10. Proposed integral initial synthesis (Andrews, 1985)

conceptual layout. The final stages evaluate the conceptual design, determining if the proposed layout is successful ('true'). If the proposed design is unsuccessful ('untrue') the approach allows for modifications to the spatial disposition and ship gross size, the remaining parts of the design are not modified. The three steps: disjunction, expansion and conjunction focussed on the integral ship design are visualized in figure 3-11.

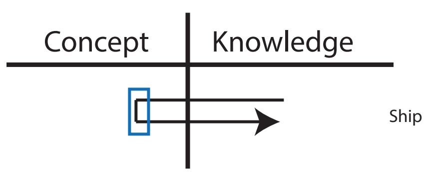


Figure 3-11. Visualization of creative ship design with respect to CK-theory, representing disjunction, expansion and conjunction

The work by Andrews allows for and is able to describe the development of creative solutions, however this work is not generic: it concentrates on the development of 'simple synthesis' designs (table 1-1) (Andrews, 1985), where concepts are only acceptable in the development of the layout of the vessel. The approach does not describe how other types of innovations, such as more extreme innovative designs or newly developed components and systems are developed.

Interestingly, the initial paper by Andrews in 1981 proposes a second research path: *"The second stimulus to creative ship design is more open. By listing some of the possible techniques to deal with the wider design tasks in the future, it has been concluded that a comprehensive design philosophy ought to be pursued. Such a philosophy needs to be open and responsive to new creative techniques whilst conscious of the real constraints in design"* (Andrews, 1981, p. 454). Still, no research in ship design appears to provide a comprehensive design philosophy which describes the development of the different innovative designs observed in practice. The second stimulus does align with the objectives of this research, as both aim towards a comprehensive design philosophy to deal with the design tasks of the future

3.2.3 Decision-based design by Mistree, et al.

Decision-based design within the ship design industry was introduced in the early 1990's (Mistree, et al., 1990) and was further developed by Erikstad (Erikstad, 1996). The approach aims to include the non-sequential nature of design and support life-cycle considerations, two considerations that were lacking in the ship design spiral (Mistree, et al., 1990) Decision-based design uses the initial principles of system thinking and concurrent engineering as an option to support life-cycle considerations and decision-making of designers (ibid.).

The system thinking and concurrent engineering approaches were primarily applied in the later stages of the product development, broadening the product development scope to include process development and prototyping (ibid.). During the initial phases (as they identify it: the meta-design) a structure is developed to control a successful mapping between decisions, performances, goals and values (Erikstad, 1996). The work on decision-based design remains focussed on the later stages of the design process, where the naval architect is involved in decision-making. During this stage, the approach sees the design as a structured problem which can be programmed, generating knowledge based on the structures developed in the meta-design.

Decision-based design does not allow for conceptual, undecided propositions after the development of the meta-design, but concentrates on generating knowledge based on structures, a process of conjunction (visualized in figure 3-12). During the meta-design new structures are developed based on decomposition, partitioning and planning activities. These structures are applied to evaluate the design problem using software applications. How the meta-design leads to creative solutions is not discussed.

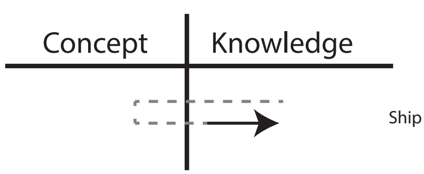


Figure 3-12. Visualization of decision based design with respect to CK-theory, representing the meta-design (dashed) and the conjunction

3.3 Systems thinking in ship design

From the early 1990's the ship design literature became more and more influenced by the system thinking approach. System thinking encompasses a broad set of processes used in development, engineering, evaluation, management and control of complex systems. The approach sees an object not as an individual entity, but as a set of subsystems with combined emergent properties (Mistree, et al., 1990).

In more complex systems such as ships and airplanes, this takes the form of a 'System-of-Systems', a definition of which the origin is unclear, but was developed for ship design in the work of Mistree, et al. (ibid.). In a system of systems a large system (for example an aircraft or ship) consists of multiple systems in their own right, which in turn consist of subsystems and components (figure 3-14, figure 3-13).

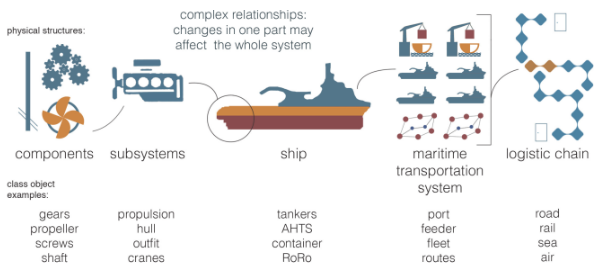


Figure 3-13. A ship as a system-of-systems (Gaspar, 2013)

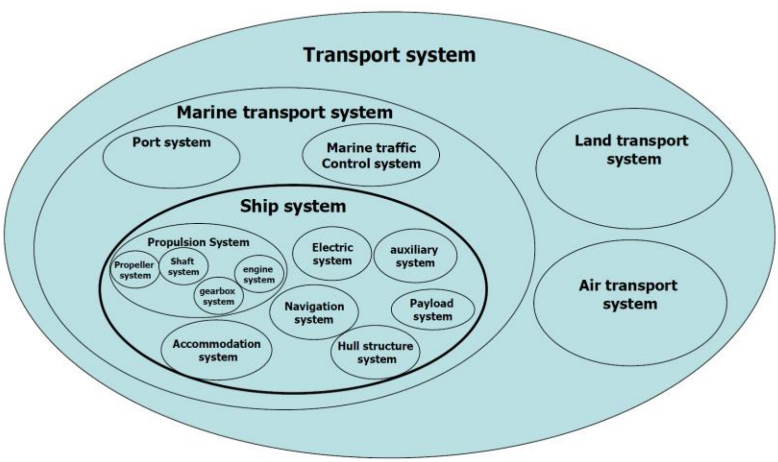


Figure 3-14. A ship as a part of a larger system, composed of smaller subsystems (Hopman, 2007)

System thinking based approaches consider a system as based on separate parts with a certain hierarchy: a system is decomposed into smaller structures, each with their own properties (figure 3-15). Such a hierarchy can be developed using different approaches, subdividing the physical ship (shown in the left side of figure 3-13) into subsystems and components, or creating a hierarchy based on specialities or disciplines (amongst others discussed in decision-based design (3.2.3) and set-based design (3.3.3)).

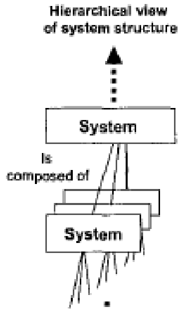


Figure 3-15. Hierarchy as a concept (ISO, 2002)

The integrated solution, consisting of multiple subsystems, has properties that are attributed to the whole and not to the sum of the parts (Checkland, 1999). This 'System of Systems' hierarchy defines an integrated structure (ship design) which is composed of multiple systems which in turn is composed of subsystems and components. Such a decomposing perspective is key in any system thinking approach.

Such an approach does not only describe the development of the overall system, in this particular case the ship design, but also allows for conceptual developments of each of the levels in the hierarchy such as the business concept, the system design and component design (visualized with respect to CK theory in figure 3-16).

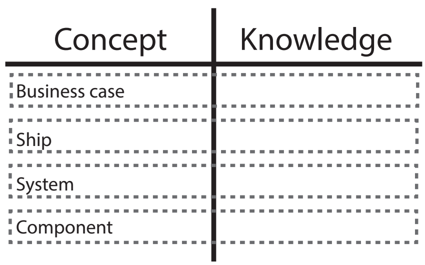


Figure 3-16. Visualization of designs at each level of decomposition, with respect to CK theory

System thinking based approaches were first documented in the early 1940's (INCOSE, 2014) and have been developed with applications in aircraft, mechanical, software and maritime engineering. The subsequent subsections discuss the ship design processes that are heavily influenced by systems thinking. The first mentioning of system thinking in ship design is in decision-based design (discussed in subsection 3.2.3), the approach primarily applied systems thinking in later stages of the development, supporting concurrent engineering. The approach is not placed in this section as the initial stages of decision-based design did not discuss how the decomposition influenced the design process. This section discusses the following strategies in ship design influenced by systems thinking and decomposition:

- System based design (3.3.1)
- System engineering (3.3.2)
- Set-based design (3.3.3)
- Functional analysis (3.3.4)
- Requirement elucidation (3.3.5)

Both functional analysis (3.3.4) and requirement elucidation (3.3.5) are part of the broader system engineering framework discussed in subsection 3.3.2, but were developed for specific applications in ship design. System based design (3.3.1) and set-based design (3.3.3) are independent developments incorporating a decomposed perspective on the vessel.

3.3.1 System based design by Levander

System based design is an approach developed to provide more design freedom while still guiding the naval architect to technically feasible solutions. The approach assumes a discrepancy between the objectives from the shipbuilder and the ship owner. The builder concentrates on the technical matters, while the owner is more interested in payload capacity and performance. The approach identifies the starting point of any design as a clear understanding of the owner's musts and wants, still, potential features that the owner is not aware of should be considered and discussed as well (Levander, 1991).

As Levander describes, the system based design approach tries to avoid iterative behaviour in the project by sizing the vessel based on capacities and tasks defined by the client's mission. The sizing is based on datasets, providing trend lines and supporting the scaling of spaces and volumes. The initial sizing of the systems provides input for the different alternative layouts. These alternatives are evaluated based on the operational performance of the vessel: the owner's perspective. After the evaluation, an alternative is selected and developed further (Levander, 1991). The approach was initially developed for cruiseships and ferries (figure 3-17), but has since then proved its value in a similar fashion for the development of offshore support vessels (Erikstad & Levander, 2012).

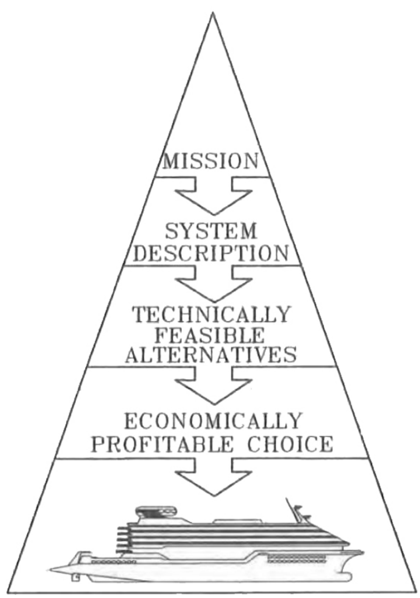


Figure 3-17. System based cruise ship design (Levander, 1991)

The system based ship design approach provides a more flexible and open approach to the design, still, the generation of experienced based data is derived from previously developed vessels, including machinery layouts, overall layouts (figure 3-18) and trend lines based on deadweight, gross tonnage and installed power of the existing fleet. The scaling of the individual systems provides more freedom to create an overall layout compared to the design spiral. The approach allows for conceptual, undecided solutions to emerge when developing technical feasible solutions. These newly developed technical feasible solutions concentrate on the overall layout (Levander, 1991) and are based on predefined systems derived from existing designs and evaluated based on a predefined, existing mission. This is visualized with respect to the CK-theory in figure 3-19.

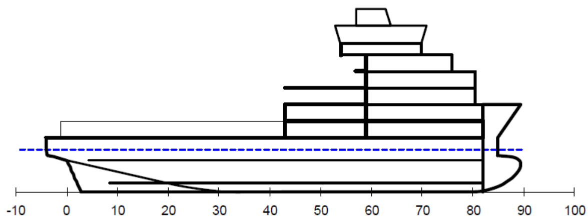


Figure 3-18. Early geometric definition in system based design (Erikstad & Levander, 2012)

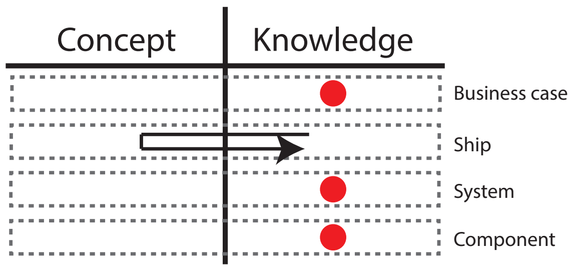


Figure 3-19. Visualization of the system based theory with respect to CK theory, representing the design on the ship design level, with existing or given systems on other levels

The approach is tested on both cruiseship and offshore supply vessel designs showing merit for application in different vessel types. However, it does not account for innovation in other parts of the ship design such as individual systems and components or conceptual business cases.

3.3.2 System engineering

One of the most well-known applications of system thinking is the system engineering (SE) framework. SE is an interdisciplinary framework supporting project management within the entire life-cycle of a complex system (DoD, 2001). The SE literature is broad as it discusses anything from initiation to decommissioning, including design, acquisition, construction and operation of large and complex systems. For the purpose of this thesis the review is limited to the development of new systems within the ship design industry. SE was initially developed for the software and aerospace industries and is since then applied to other engineering disciplines, leading to little common ground in different technical and managerial methods. There are many representations of SE within ship design, the most common representation is the V-diagram shown in figure 3-20.

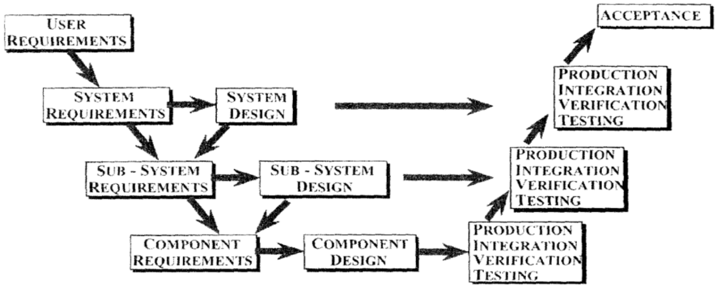


Figure 3-20. System engineering V-diagram (Griethuysen, 2000)

According to Griethuysen, SE suggests that system design precedes subsystem design (as visualized figure 3-20): an assumption that is not always valid in ship design (Griethuysen, 2000). He still sees SE as a valuable addition to the engineering process, but one that should be tailored to specific applications, products and engineering communities, for example by taking into account the physical aspects of the design of complex products (ibid.). Even though there is little common ground within the broad SE literature, the design of sublevels is usually described as containing four generic steps: (1) requirement analysis, (2) functional analysis and allocation, (3) design synthesis and (4) system analysis and control (for example shown in the representation in figure 3-21).

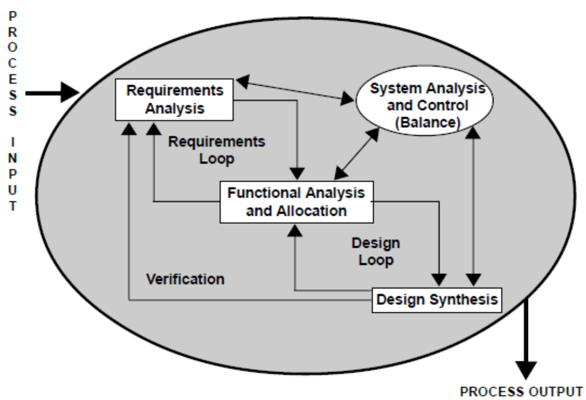


Figure 3-21. Design of a level (DoD, 2001)

The application of overall SE principles in ship design are discussed by both the work of Brown & Thomas and by Griethuysen (Brown & Thomas, 1998; Griethuysen, 2000). Later publications discuss specific activities in SE, in particular the functional allocation (discussed in more detail in section 3.3.4) and requirement analysis (discussed in more detail in section 3.3.5). The work of Brown & Thomas primarily concentrates on the search for feasible concepts optimal for an overall measure of effectiveness. To support this process a new design framework is introduced which describes the design process as the mapping between four domains: the (1) customer (2), functional, (3) physical and (4) process domains, based on the mapping approach defined by Suh in the early 90's (Suh, 1990). Each domain is represented by a hierarchic structure with design described as the mapping process between these hierarchic structures in the four domains. Griethuysen in his paper discusses that SE provides a generalized framework to consolidate the development of large and complex systems. The approach needs to be tailored to specific applications, for example ship design. It is argued that naval architects already applied SE principles, without identifying them as such (Griethuysen, 2000).

The SE framework is currently applied in both the naval ship design and commercial vessels (Griethuysen, 2000; DoD, 2001; Andrews, 2012; Krikke & Stroo-Moredo, 2013). SE is a generic framework based on existing structures which may contain conceptual developments (Andrews, et al., 2009). The framework itself does not describe how the conceptual or undecided propositions are handled during the design process. Furthermore, Griethuysen identified the sequential approach in developing systems, subsystems and components, an assumption that is not always true in ship design, as such it may limit creativity in lower levels of decomposition (Griethuysen, 2000).

SE is one of the most extensive applications of system thinking aiming to consolidate and improve the project management throughout the life-cycle of a complex system. The framework may contain conceptual solutions on different levels of decomposition, although it does not describe how these conceptual developments are created or occur. The top-down structure of SE could be applied to provide a framework although current developments focus on consolidating the developments on each individual level of decomposition. These steps can either develop from existing knowledge or from concepts, but they concentrate on further improving knowledge on each level (conjunction, visualized with respect to CK theory in figure 3-22).

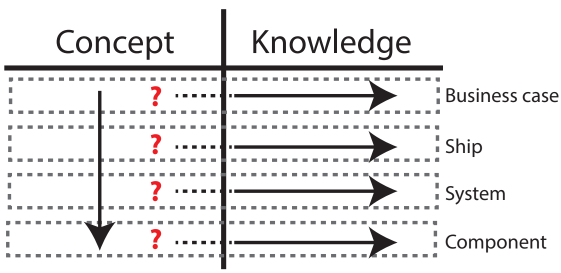


Figure 3-22. Visualization of the system engineering with respect to CK theory, representing sequential, top-down conjunction of individual systems

3.3.3 Set-based design by Parsons and Singer

Set-based design is a design strategy developed to complement concurrent engineering, to provide a greater probability of achieving a global optimum for the overall design (Parsons, et al., 1999). The approach is a response to the point based design approaches described in section 3.2 based on a single design. Set-based develops and evaluates a set of designs based on a broad sets of design parameters to allow for concurrent developments. These broad sets of design parameters are structured by specialty, resulting in a conceptual, hierarchical decomposition of the design. These broad sets of design parameters are gradually narrowed when trade-off information becomes available, until a more global optimum solution is revealed and refined. This increases the level of detail and the fidelity of the design.

The design strategy was developed within Toyota to improve the design of new cars (Ward, et al., 1995; Morgan & Liker, 2006). The ship design applications were first mentioned in 1999 to support concurrent engineering and the development of integrated product teams (Parsons, et al., 1999). Set-based design supports the exploration of more design alternatives as options are kept open longer to increase insight in the overall design (Singer, et al., 2009), (figure 3-23). This approach feels counterintuitive, as more time is required in the early stages of the design, but the approach eliminates iterative paths found in point based approaches, improving the design process in later stages (Wolff, 2000). Recent developments applied set-based design within naval ship design (Singer, et al., 2009; Mebane, et al., 2011) and MSc students (Bernstein, 1998), (Frye, 2010).

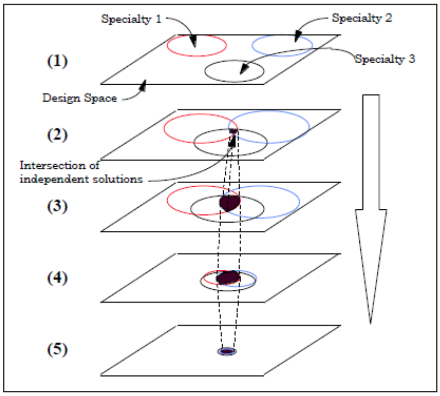


Figure 3-23. Representation of three specialties converging in set-based design (Bernstein, 1998)

The work of Brown also applies different sets in developing a new ship design (Brown & Thomas, 1998; Brown & Waltham-Sajdak, 2014). The approach does apply set-based integration and conversion technique. Although it is not described as set-based design, the approach splits the initial baseline design into several specialities (6 in total, as shown in figure 3-24) which are developed into a single design. This provides some insight in applying set-based design practices in the ship design industry.

Set-based design aims to improve design discovery in the early stages of the design process. The approach uses sets of design parameters, usually linked to specialties to generate new concepts (figure 3-23). When sufficient knowledge is available, these sets are merged into a single, overall design. Set-based design creates a conceptual decomposition, and subsequently allows for multiple concepts to coexist in these ‘sets’ of design parameters, until a decision is made based on the newly developed knowledge; an approach new to the industry. The approach concentrates on the conjunction of systems: bringing them from (multiple) concepts through a well-defined process into the knowledge space, a process visualized in figure 3-25.

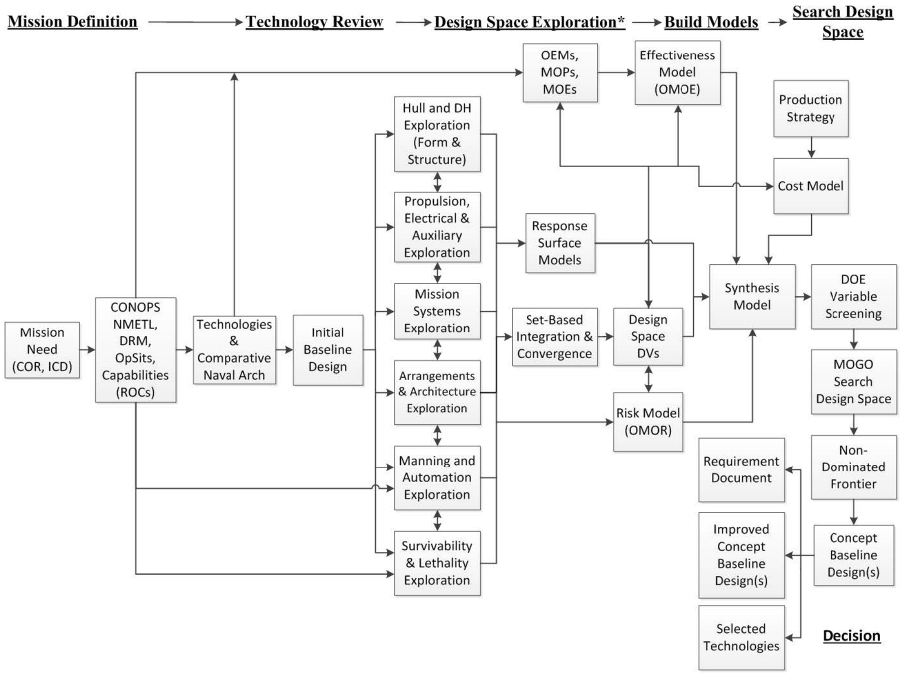


Figure 3-24. The naval ship concept design process (Brown & Waltham-Sajdak, 2014)

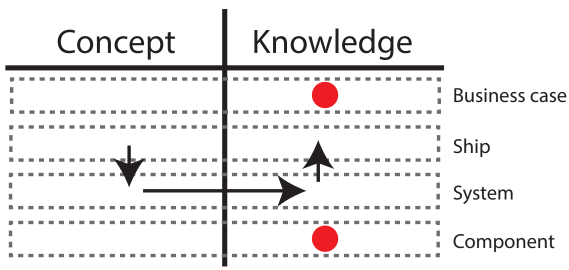


Figure 3-25. Visualization of set-based design with respect to CK theory, representing conjunction of systems and integration into the ship design based on increased knowledge

The approach is the first that explicitly allows multiple concepts to coexist without directly concentrating on evaluating or selecting the most feasible option, an approach which is could be valuable in describing how conceptual solutions are handled.

3.3.4 Functional analysis by Wolff

The SE approach discussed in subsection 3.3.2 initiated several investigations aimed at the development of specific ship design tools within the SE framework. In 2000 a PhD research was published concentrating on the function analysis to support and improve development of warships of original design (Wolff, 2000). The approach concentrates on designs which do not have a parent design or fixed functional requirements, but have an ordinal system of utilities, multiple functions with relations among them and a high degree of uncertainty and unforeseen aspects (Wolff, 2000).

The work of Wolff concentrates on the functional analysis (figure 3-26) as a top-down design process, allowing for original design. It concludes that the functional analysis is primarily a method of analysing the goals of an object of design: the role of functional analysis in generating alternatives is limited, except for minimizing concepts that do not fit into the goal structure. Wolff continues his work concentrating on the development of an information structure that supports the development over the different stages to reduce the effects of the iterative behaviour and improve the quality of the design.

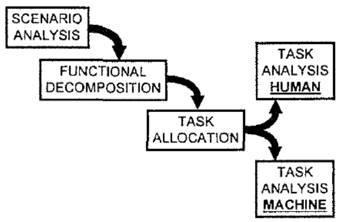


Figure 3-26. Waterfall model of the functional analysis (Wolff, 2000)

The structure used for function analysis, a functional decomposition such as shown in figure 3-27, is described as a top-down design process that, according to its creator allows for original design.

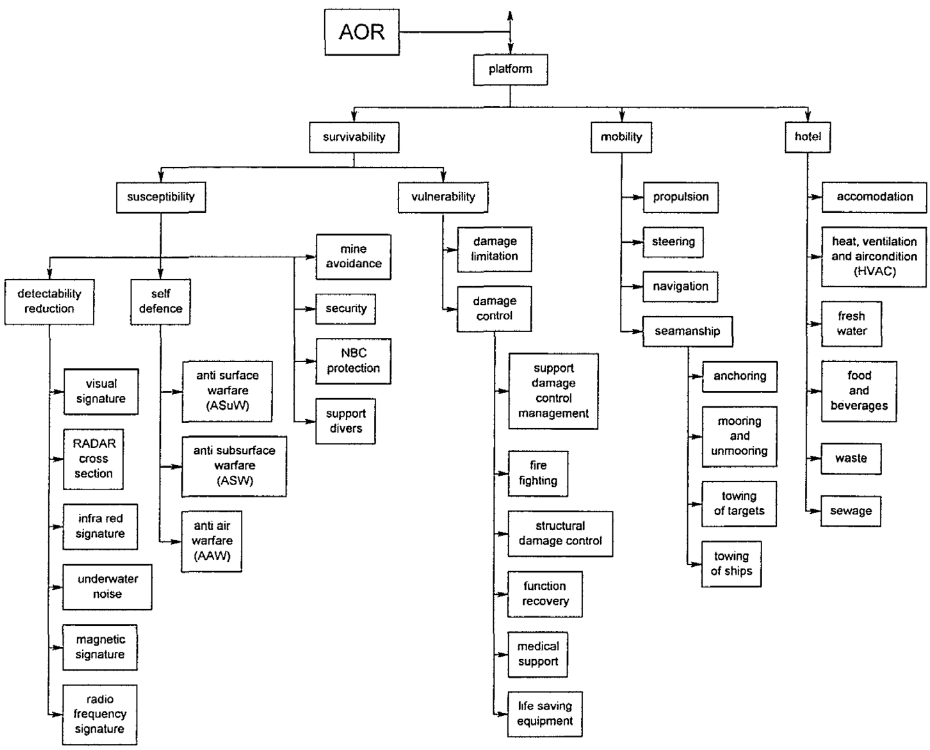


Figure 3-27. Decomposition of a replenishment-oiler (AOR) (Wolff, 2000)

The function analysis or the development of the functional breakdown structure has been applied in both naval ship design as well as commercial ship design (Krikke & Stroo-Moredo, 2013). Although the approach is described as design process, Wollff recognized that the formalized, sequential steps are not followed in reality, as he states: *"not even under "perfect design" conditions"* (Wolff, 2000, p. 165). This correlates with work in system engineering (Griethuysen, 2000) and axiomatic design (Suh, 1990), both describe the development of the functional breakdown as highly dependent on the selected solutions (the interaction between the design and the functional requirement structure are visualized in figure 3-20, concentrating on SE).

The applicability of functional analysis as an encompassing design tool describing creative and innovative design appears to be limited (Wolff, 2000), according to him, the structure does not reflect the design strategy observed in practice. Still, the functional analysis approach does provide insight in the partitioning of conceptual functions, an activity in the conceptual space to handle more complex undecided propositions (as visualized in figure 3-28). Interestingly, this partitioning activity appears to be influenced by the selected solutions, as discussed by Griethuysen (Griethuysen, 2000). The influence of the solution on the partitioning activity results in a more complex approach to decomposition than currently described, as the structures of the functional decomposition and the physical structure interact.

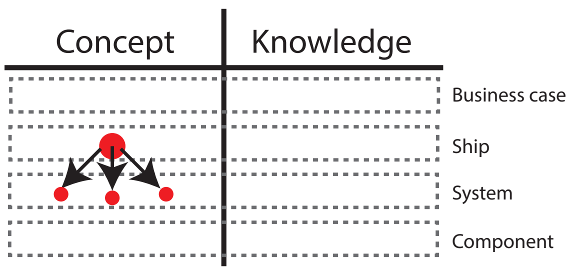


Figure 3-28. Visualization of functional analysis with respect to CK theory, representing partitioning

3.3.5 Requirements elucidation by Andrews

The work on requirement elucidation discusses the creative steps lacking from the system engineering framework. Requirement elucidation concentrates on the early phases of the System Engineering process, a phase often identified as the requirements engineering (Andrews, 2004). The approach focusses on the interaction between the requirement owner, often the client, and the naval architect. The interaction is necessary to codevelop both the requirements and the ship design (ibid.). The work on requirement elucidation identifies that defining requirements without solutions result in poor systems engineering. Therefore a change is proposed from requirement engineering to requirement and naval architectural capability (Andrews, 2011). The requirement elucidation approach requires a comprehensive, architectural driven solution to develop the physical solution in coherence with the requirements. The architectural approach and the related software tools are developed further in the building block approach, discussed in 3.4.1 (Pawling, 2007).

During requirement elucidation the solutions and requirements are developed in parallel, as shown with respect to CK theory in figure 3-29. Both in the business case and the ship design conceptual developments take place.

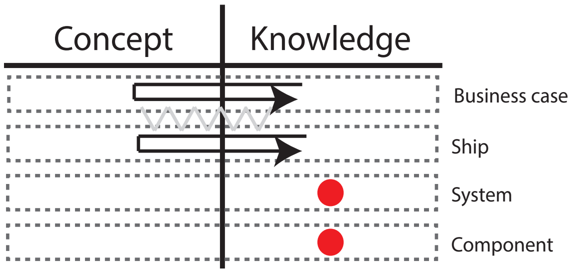


Figure 3-29. Visualization of requirement elucidation with respect to CK theory, representing disjunction, expansion and conjunction in both the business case and the ship design, while developing in parallel

Requirement elucidation supports the parallel development of business requirements and ship design: This is the first approach that allows undecided propositions or concepts on both levels of decomposition. How the business requirements and ship concepts influence each other is not clarified within this theory.

In a subsequent development on requirements elucidation Andrews introduces system architecting as an alternative to system engineering that may be better supporting in ship design (Andrews, 2012). System architecting or is a system thinking based approach that concentrates on the development of organisations, relationships and ill-structured problems (Maier & Rechtin, 2000). System architecture, the development of the conceptual and physical structures describing the overall design has not been explored within the ship design industry. The approach separates itself from system engineering approaches (3.3.2) by concentrating on the initial development of complex systems and structures. This places system engineering and systems architecting on opposite ends of the spectrum of systems thinking (Maier & Rechtin, 2000), (table 3-1).

Table 3-1. The architecting - engineering continuum (based on (Maier & Rechtin, 2000))

Characteristic	*Architecting*	<---->	*Engineering*
Situation	Ill-structured		Understood
Goals	Satisfaction		Opzimation
Methods	Heuristics Synthesis		Equations Analysis
Interfaces	Focus on misfits		Completeness
System-integrity maintained through	Single Mind		Diciplined methodology and process
Management issues	Working for the client, Conceptualization and certifcation, Confidentiality		Working for builder, Meeting project requirements, Proft vs. costs

Systems architecting highlights the role of the designer (or naval architect) as sociotechnical actor (Maier & Rechtin, 2000). It explores the cooperation between the client and the system designer, the object and the surrounding social system. Instead of optimization and detailing, the approach aims for fit, balance and compromise of the architecture between the client's needs, resources, available technology and stakeholder interest. It has been applied in the development Ultra Large Scale (Software) Systems. In these fields the system architecting approaches manage the social and technological challenges: the open development of structures and the management of the architectures.

The solution to these 'wicked' problems is based on combining both system engineering and systems thinking (Sillitto, 2010), splitting the problem situation in a part that can be solved with existing and known solutions and a part that needs to be managed, requiring solutions that are yet unknown. Systems architecting might provide a framework to describe creativity in ship design, but there are no applications of systems architecting available in the ship design literature, except for a paper suggesting to explore this field further (Andrews, 2012). The approach appears to focus on the creativity in the design, taking into account the broad spectrum of innovative solutions (Crawley, 2007). Systems architecting makes a distinction between the elements developed within existing knowledge (within K-space); elements that are 'true' and elements that require concepts; elements that are still 'undecided' within a project, with both elements requiring a different approach in development and management, as visualized with respect to the CK theory in figure 3-30.

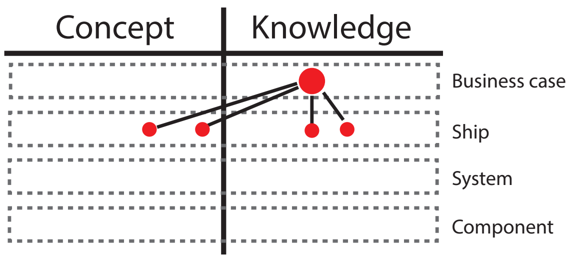


Figure 3-30. Visualization of system architecting with respect to CK theory, representing the partitioning into elements that are conceptual and elements that can be developed within the knowledge space.

3.4 Creative techniques, software tools and methods in ship design

The ship design industry applies a wide range of designated software tools to develop and evaluate ship designs. To limit the scope of this review this section concentrates on ship design tools that aim to support creative ship design. Several other tools are not discussed in this section as they are tools that aim to reduce time and costs by automating repetitive, non-creative tasks (La Rocca, 2010), for example: tools supporting reuse of components and platforms such modularization and platform thinking (Erikstad, 2009; Nieuwenhuis, 2013), knowledge based tools design (van Hees, 1997; van der Nat, 1999) or optimization (Hockberger, 1996).

The following tools appear to accommodate creativity better, the tools and techniques discussed in this section accommodate the creative layout development (Pawling, 2007), generate new layouts using a genetic algorithm (van Oers, 2011) and support the evaluation of creative solutions (Gaspar, et al., 2013).

3.4.1 Design building blocks by Pawling

The design building block approach is based on the developments in creative ship design (3.2.2) and the more recent requirement elucidation (3.3.5). Both approaches advocate and require tools to support the quick configuration of a design to support requirement elucidation. This tool is further developed and tested during the PhD research of Pawling and implemented in Paramarine software (Pawling, 2007). The tool, initially developed under the name Subcon (submarines, (Andrews, et al., 1996)) and Surfcon (surface vessels, (Andrews & Dicks, 1997)) makes it possible to develop new vessel layouts based on existing building blocks (figure 3-31).

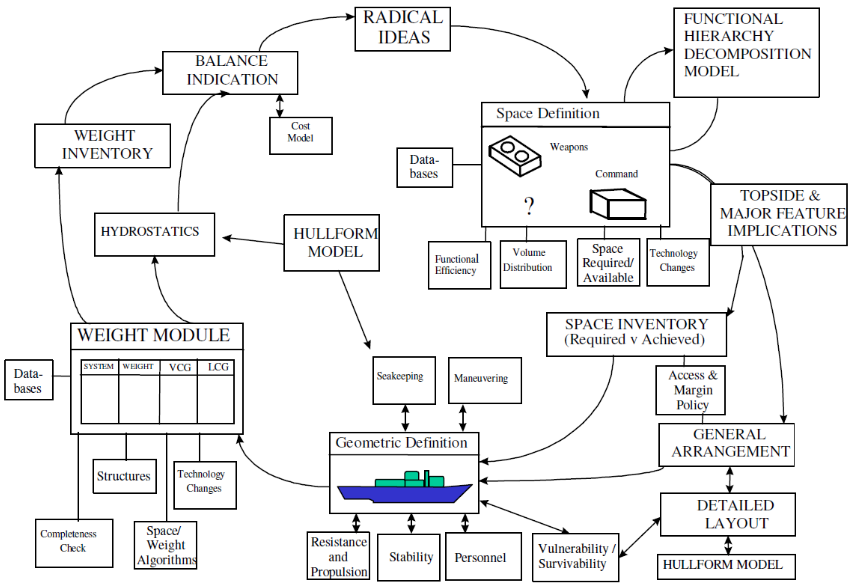


Figure 3-31. Surfcon process (Andrews & Dicks, 1997)

The approach has been developed in a wide range of naval ship design projects and bachelor and master student projects, developing concepts and testing the tool (Pawling, 2007; Pawling & Andrews, 2009), (figure 3-32).

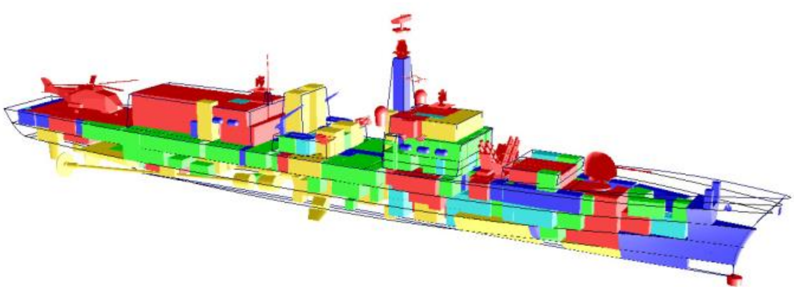


Figure 3-32. A building block approach development (Pawling, 2007)

The building block approach provides a flexible and open environment to develop and foster creative ideas based on existing building blocks, as shown in figure 3-33. The tool makes it possible to quickly generate conceptual layouts based on existing systems to support the interaction between the ship designer and the requirement owner. The tool is based on existing systems and components, and does not take changing business cases into account. The visualization shows the design process on the ship design level with respect to the CK-theory.

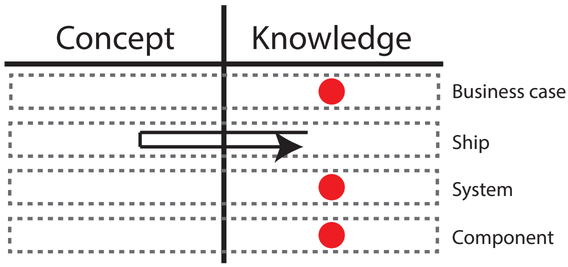


Figure 3-33. Visualization of the design building block approach with respect to CK theory, representing the design on the ship design level, with existing systems on other levels

3.4.2 Packing by Van Oers

The tools for packing (van Oers, 2011) were developed to generate the layout of vessels automatically during the early stages of the design process. Packing is based on system engineering described with the V-diagram shown in figure 3-34. This model is introduced as the process naval architects use to guide their design effort, concentrating on the integration of subsystems and components into a valid, evaluated configuration.

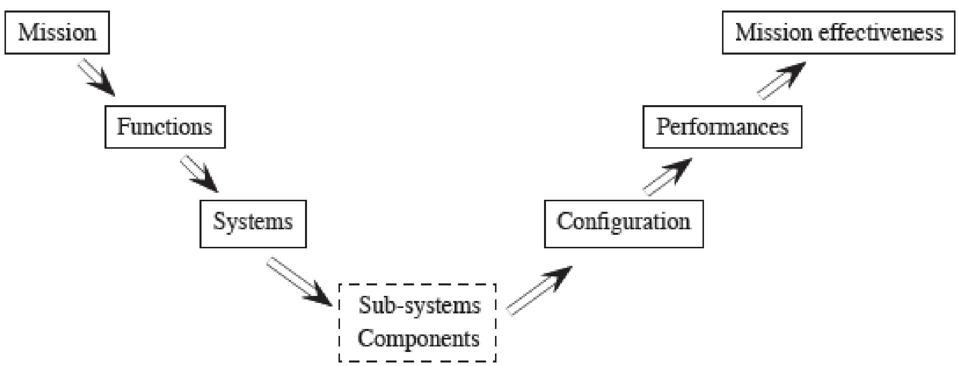


Figure 3-34. System engineering V-diagram (van Oers, 2011)

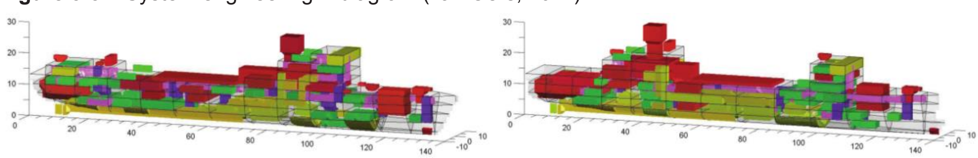


Figure 3-35. Example of a parametric model of a frigate with two different arrangements (van Oers, 2011)

The approach develops a layout based on a known set of subsystems and components with known boundaries and interfaces to their direct environment. These components are intelligently placed by a genetic algorithm to develop feasible solutions. The feasible solutions are determined with tools calculating stability, motions and speed/power. The design varies within predefined boundaries, such as hull type, length and width and boundaries based on the requirements of the components and subsystems. Figure 3-35 shows two different arrangements that result from applying this packing tool.

The V-diagram presented in figure 3-34 is based on the system engineering V-diagram (van Oers, 2011). Although this V-diagram identifies the importance of the interactions between the different levels of decomposition, it does not illustrate how these interactions occur, nor what happens between these different levels of decompositions. The tools both concentrate on the automatic generation and evaluation of concepts by applying genetic algorithms: both tools optimize within a predefined, existing framework, a framework that is governed by propositions that are either true or false (and therefore can be implemented in a software application). Both tools focus on the optimization of the overall layout based on existing systems, an integration step, based on an existing knowledgebase; all within the K-space and not on the development of new, conceptual solutions. This is visualized with respect to CK theory in figure 3-36. The approach sketched as a description of the design process identifies the importance and interaction beyond the original system boundaries defined in classical system engineering, potentially allowing for developments at multiple levels of decomposition.

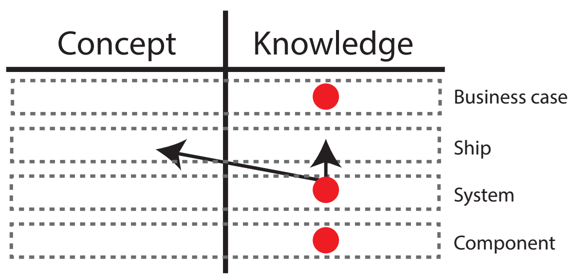


Figure 3-36. Visualization of the packing and intelligent layout software with respect to CK theory, concentrating on the integration of existing system levels into a ship

3.4.3 Complex systems approach in ship design by Gaspar

The complex systems theory is applied within the ship design industry to handle the complexity of conceptual ship design. The approach identifies 5 aspects in complex systems to determine the complexity in conceptual ship design (Gaspar, et al., 2013). The five aspect taxonomy approach, initially developed at MIT (figure 3-37, (Rhodes & Ross, 2010)) concentrates on the analysis and optimization in system design, with an emphasis on the early assessment of predictability, cost, operability, robustness and risk (Gaspar, et al., 2013).

The approach defines an individual system as dependent on 5 aspects: structural, behavioural, contextual, temporal and perceptual. These aspects are evaluated using epoch-(or 'era') analysis (an analysis over a longer period of time) to cover uncertainty in future scenarios, in particular exploring contextual, temporal and perceptual aspects. The structural and behavioural aspects are not developed further within complex system theory, as they are already discussed in other ship design literature (Gaspar, 2013).

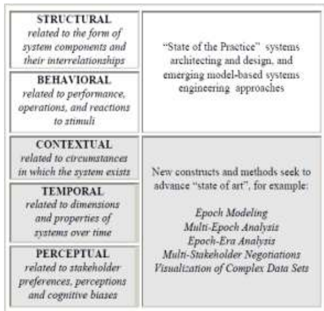


Figure 3-37. Complex systems theory (Rhodes & Ross, 2010)

The complex systems theory makes it possible to structure and manage the complex character of conceptual ship design by applying the five aspect taxonomy to the evaluation of the ship design. The approach evaluates an individual system, independent if it is newly developed or pre-existing. The approach concentrates on conjunction: identifying new knowledge based on either existing designs or conceptual designs. The approach does not describe the development of the concepts. This is visualized with respect to the CK theory in figure 3-38.

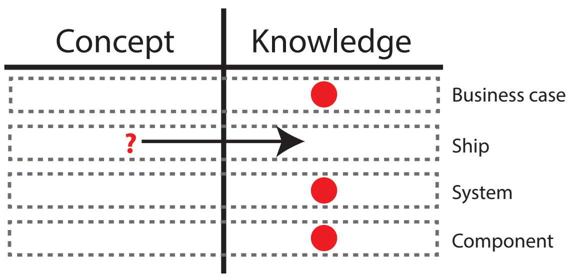


Figure 3-38. Visualization of the complex systems theory with respect to CK theory, visualizing conjunction

3.5 Summarizing the state-of-the art in ship design literature

The different theories in the current state-of-the-art in ship design are reviewed using a lens which applies CK-theory to identify creativity and innovation in each description of the design process.

The current design methodologies available for ship design do not describe the full scope of creative activities in more complex systems, but in general concentrate on a part of the creative process and/or a single level of decomposition. Several theories focus on conjunction (such as the design spiral (3.2.1) decision-based design (3.2.3), system engineering (3.3.2), set-based design (3.3.3)) aiming to develop concepts into knowledge. Other theories concentrate more on partitioning in the C-space such as Functional analysis (3.3.4) or partitioning with the aim to define both concepts and knowledge based developments in System architecting (3.3.5). Creative ship design (3.2.2), system based design (3.3.1) and requirement elucidation (3.3.5) explore the broader scope of creative development. These allow for conceptual solutions to develop either on a ship design level (creative ship design and system based design) or allow for conceptual developments of the business concept and the ship design (requirement elucidation), yet it does not provide insight in the interaction beyond the system boundaries or discusses if this interaction is generic to the interaction between other levels of decomposition.

The theories and methods discussed in this chapter show a shift from design methodology concentrating on the ship design as a single object towards a more system thinking oriented approach to handle the more complex nature of ship design, including its wider context. Such a system thinking based approach not only makes it possible to handle complexity by decomposition, but also makes it possible to describe ship design based on the creative, innovative solutions on each of the individual levels of decomposition, which could be very beneficial when reviewing the current state of practice. To visualize the creative, innovative solutions the concept of hierarchy (discussed in section 3.3 and visualized in figure 3-15) is applied to the ship design (figure 3-13, 3-14) to visualize the content of different levels of decomposition in figure 3-39.

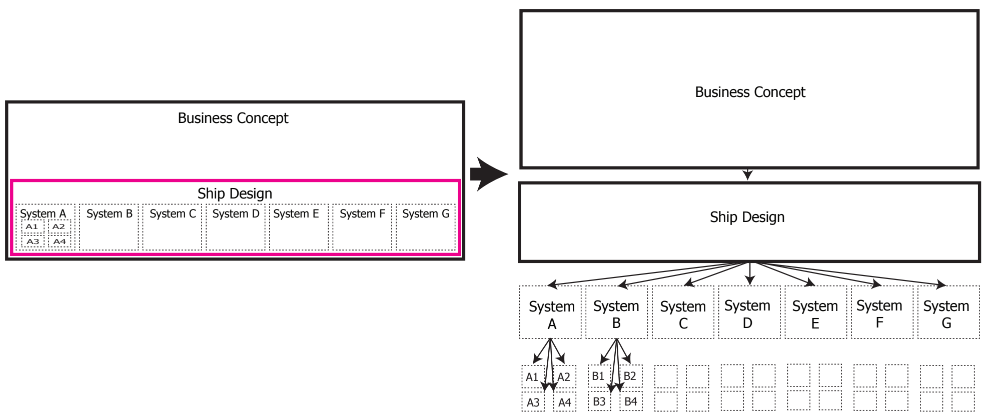


Figure 3-39. Applying hierarchy and decomposition to evaluate an existing vessel

Finally, different theories recognize the importance of the interaction between different levels of decomposition beyond their own system boundaries, for example by describing this effect as mapping (discussed in section 3.3.2) or by identifying dependencies between different levels of decomposition (discussed in section 3.4.2). Still, the current literature does not provide insight in how these dependencies occur between different levels of decomposition. Defining these dependencies based on observations from practice could provide additional insight in how innovative solutions are developed. The sequent chapter aims to complement these observations by reviewing the current state of practice applying hierarchy and decomposition (figure 3-39) on several existing, innovative ship designs.

Chapter 4

Ship design in practice: case studies into ship design

"Exploring the current state-of-the-art in innovative ship design practice"

For the benefit of the institution of the problem in the Deweyan inquiry the theoretical review in chapter 3 is complemented with input from practice (figure 4-1). This chapter provides a description of the four cases which are applied to further institute the problem. An analysis of the cases is provided in chapter 5.

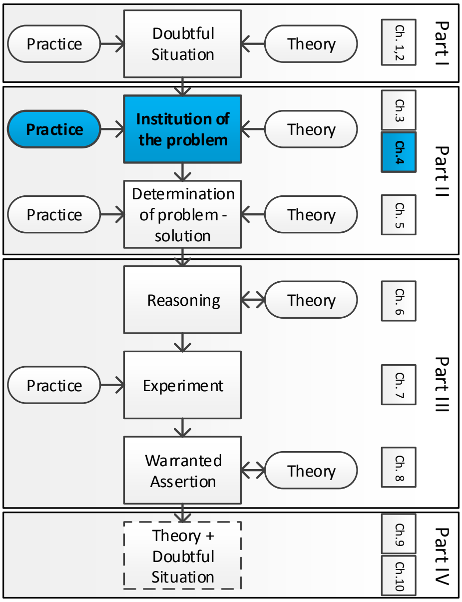


Figure 4-1. Overview of the research stages (equivalent to figure 2-6)

Four case studies are used to review the development of different vessels considered innovative in their respective markets. The case studies aim to identify the innovative and conceptual elements within these vessels and to determine commonalities between the approaches taken by the respective design teams in handling these conceptual and undecided elements. The cases are analysed applying observations from chapter 3. The selection of the cases, the lens and the case study approach are discussed in section 4.1. The subsequent sections describe and review the four individual cases (4.2 - 4.5): Each section introduces the case, identifies the conceptual items in the design and provides a description of the effort related to these conceptual elements. The final section draws cross-case observations (4.6), which are further developed in chapter 5 (figure 4-2).

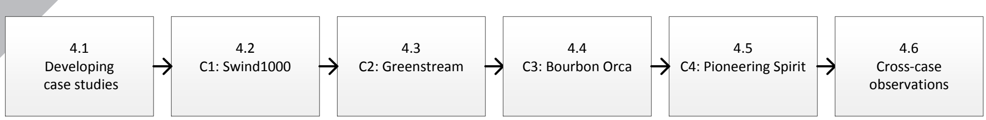


Figure 4-2. An overview of chapter 4

4.1 Developing case studies

To explore the current state of practice four case studies are selected (4.1.1) and evaluated based on a further development of the CK-theory based lens introduced in section 3.1.2, complemented with the system thinking theory discussed in section 3.5 (4.1.2). The cases are developed based on the case study protocol described in section 4.1.3.

4.1.1 Case selection

The introduction to this research in chapter 1 discussed the broad spectrum of innovative solutions seen within practice, yet a methodological approach that is sufficiently generic to describe the development of different ships and innovative content seen in practice is not available as shown in chapter 3. To explore the current state of practice further four vessels are selected as case studies. The vessels are different in type and operation, but each is considered innovative. The amount of innovation in each design is different: based on the available information at the onset the case studies are ranked from incremental innovation to radical innovation, visualized in figure 4-3. The amount of cases is limited, but due to the exploratory nature of this research, where describing and identifying has a more important role the four cases are expected to be sufficient at this stage of the research. When validating or verifying results, more cases would be preferable.

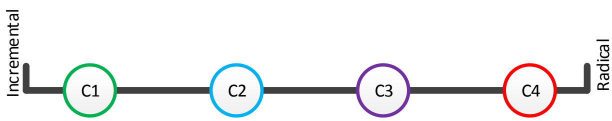


Figure 4-3. The case studies and their position on a scale from incremental to radical innovation

Case study C1 is based on a ship design with modifications to components, case study C2 and C3 are both based on ship designs with new and innovative systems. The final case study, C4, is seen as radical ship design, which is expected to change the rules of the industry. The considerations for selecting each individual case are discussed below: the first vessel is based on a project I was involved in at Ulstein (USoS), the other vessels are selected based on publications on innovative ship designs.

The first case study, **C1: SWind1000** (figure 4-4) is a windfarm installation vessel developed by USoS based on a vessel from the USoS-portfolio. The deck equipment was developed by Ulstein IDEA Equipment Solutions (UIES), which included exploration work on components specific for the offshore wind installation. The SWind1000 is a sister vessel to the offshore construction vessels (OCV) Seven Borealis and Aegir delivered in 2012 and 2013 respectively. The deck equipment was based on previous projects developed in collaboration between USoS and UIES focussing on the offshore wind industry.

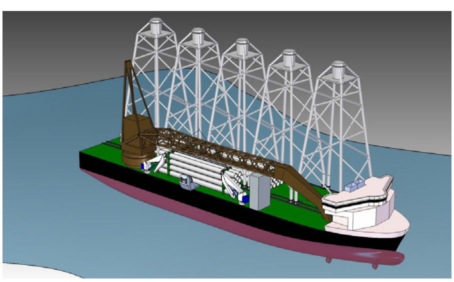


Figure 4-4. The Swind1000

The second case study, **C2: Greenstream** (figure 4-5) is the first 100%-LNG-powered inland shipping barge in the world. The vessel is developed by Peters shipyard and won the KNVTS ship of the year award in 2013, where the jury report identified innovations as the hull form, structure and the LNG / Electric propulsion plant and listed them as impressive. The vessel currently operates under a time charter for Shell (KNVTS, 2013).

Figure 4-5. The Greenstream: The first 100%, LNG-powered inland shipping vessel

The third case study, **C3: Bourbon Orca** (figure 4-6) was the first anchor handling tug and supply vessel (AHTS-vessel) with an X-Bow® developed by Ulstein Design & Solution AS (UDS, Norway). The vessel was considered a substantial innovation in several key systems as it included a new hull form, diesel-electric propulsion and the safe anchor handling system (SAHS). The vessel operates in the conventional anchor-handling, towing and supply industry.

Figure 4-6. The Bourbon Orca: The First X-bow®, Diesel Electric Anchor Handling vessel

The final case study, **C4: Pioneering Spirit** (formerly known as the Pieter Schelte) (figure 4-7), is considered one of the most radical designs of the recent years. The original design linked two very large crude carriers (VLCC's) into a catamaran, to commission and decommission large offshore platforms in a single lift. The vessel differs to other approaches and is expected to have major influence on the decommissioning and commissioning market and thereby changing the industry (Wilby, 2014).

Figure 4-7. The Pioneering Spirit: A split bow platform decommissioning vessel

4.1.2 Building a lens, expanding the framework for analysis

The review of the case studies aims to determine the creative and innovative elements in each vessel considered 'innovative' by its market, it further explores how these creative and innovative elements are handled. The initial lens, based on CK-theory, supports the identification of creative and innovative steps in the design process. However, to identify the 'undecided' or conceptual objects in each vessel the lens has to be refined.

The previous chapter described how design strategies developed from general ship design methodology towards system thinking based approaches. Such approaches enabled the handling of more complex systems by decomposing them in smaller parts: A ship is decomposed into systems, subsystems and components while it is part of a large marine transportation system or business case. More details about the system thinking in ship design are discussed in section 3.3. The decomposing approach, where an integrated finished design is decomposed hierarchically into smaller systems, subsystems and components (Checkland, 1999) is applied in the case studies to identify the undecided or conceptual items in the early stage of the design. In the cases, four levels of decomposition levels are defined: business case (of which the ship is a part of), ship design, system design and component design. The decomposing approach, resulting in a hierarchical structure is visualized in figure 4-8.

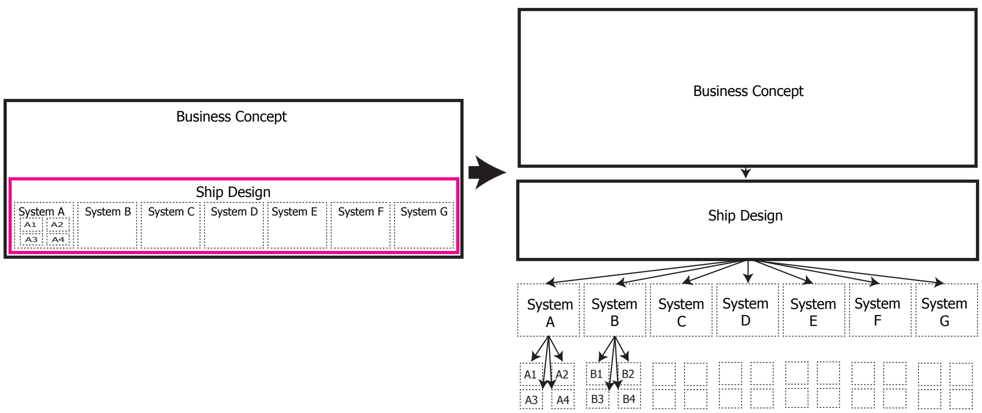


Figure 4-8. From an integrated design (left) to a hierarchical structure (right) (similar to figure 3-39)

The lens developed in section 3.1.2 is applied to the hierarchical structure to identify which elements were, in the early design phases of the project 'undecided' and would be acceptable whether they are true or false, with a high degree of uncertainty. These undecided or conceptual elements are visualized in the C-Space, other elements which are known in the early stages are visualized in the K-Space. An example of such a visualisation is shown in figure 4-9, it identifies conceptual ship design, based on existing systems and components and is developed for an existing business case.

The identification of the conceptual elements in each design provides the starting point to discuss how these elements are handled throughout the development.

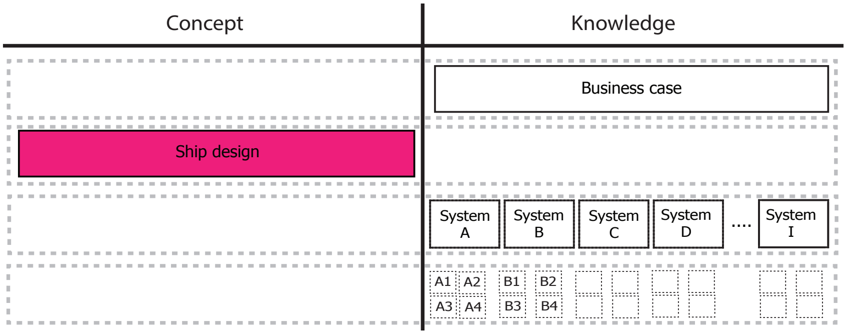


Figure 4-9. An example of identifying concepts: conceptual ship design illustrated in fuchsia

4.1.3 Case study procedure

The case studies are developed according the case study research protocol provided by Yin (Yin, 1994), discussed in more detail in subsection 2.3.3. The five steps identified by the protocol are shown in figure 4-10. Where to find the related data to each step in the case study protocol is illustrated in table 4-1.

Figure 4-10. Case study procedure (Yin, 1994) (similar to figure 2-5)

Table 4-1. Steps in the case procedure and the related data

Step		C1:	C2:	C3:	C4:
1	Framework	Section 4.1.2			
2	Case selection	Section 4.1.1			
3	Data collection	Section 4.2	Section 4.3	Section 4.4	Section 4.5
4	Case reporting	section 4.2.1-4.2.3	section 4.3.1-4.3.3	section 4.4.1-4.4.3	section 4.5.1-4.5.3
5	Cross-case conclusions:	Section 4.6			

Each case is described in more detail in the case study reports: these reports are commercial in confidence, for access or more information please contact the author of this dissertation. A complete review of the cases is not preferable, therefore a summary of the case studies is presented here. Each individual case is based on a dataset consisting of available design data, publications and other sources.

A key source of information are the interviews conducted for each case study. The interviews are conducted in an open manner, making it possible to explore the experiences of the involved naval architects, client's and technology partners during the developments. The interviews are transcripted, based on these transcripts quotes are derived and, if necessary, translated from Dutch to English. To improve readability the quotes are restructured; this was possible as the interviews concentrated on the content and not on the social aspects observed during the interviews. To reduce the influence of the researcher, all restructured quotes are reviewed and approved by the interviewees (figure 4-11).

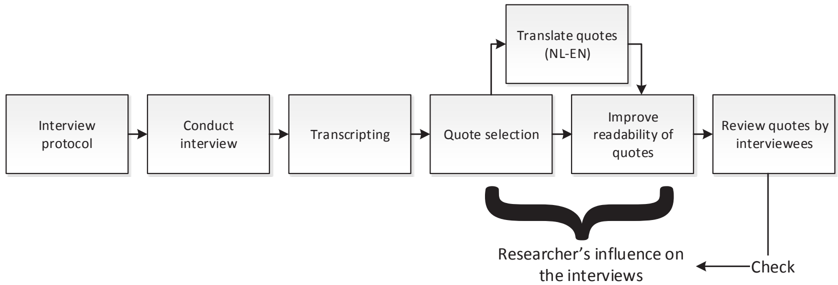


Figure 4-11. Overview of interview analysis

4.2 C1: Swind1000

The SWind1000 was developed by Ulstein Sea of Solutions (USoS) for a company involved in offshore oil and gas who wanted to explore a possible new build for offshore windfarm installation. The design was based on the SOC5000 design from the USoS portfolio: an in-house development for a generic offshore construction vessel (OCV). Modifications to the SOC5000 design already lead to two vessels, currently in operation: the Seven Borealis (Ulstein Sea of Solutions, 2012b) and the Aegir (Ulstein Sea of Solutions, 2012c), shown in figure 4-12.

Figure 4-12. The Seven Borealis (left) and the Aegir (right)

The SWind1000 was developed in close collaboration with USoS's sister company, Ulstein Idea Equipment Solutions (UIES); based on a previous cooperation for another client in the same market. The development was further supported by companies with specific knowledge in economic analysis and crane development. The project was developed in approximately 5.5 months, from the kick-off meeting in June 2012 until the delivery of the final documentation at the end of the project in December 2012.

The involved team within USoS was small; the design was developed by a project manager supported by myself: The project was a hands-on experience as a researcher/practitioner: I was the naval architect involved throughout the project, in meetings, documentation, design tasks and analysis. This provided me access to all design documentation and insight in the current projects. My personal observations are documented in a diary. Although the client was pleased with the final design, the vessel was not built as the company decided not to pursue offshore wind installation as a business case.

The case description provided here is based on an extensive dataset including an interview with the project manager of Ulstein Idea Equipment Solutions, project related e-mails, design documentation, the final design, project initiation documents, project management documents and observations; summarized in table 4-2. The documentation is stored to support retrieval when necessary.

Table 4-2. Dataset, case C1, Swind1000-design

Type	Amount
1. Interview	1 interview, 28m, 36s
2. Project related e-mails	184 project related e-mails
3. Design documentation	1.141 files
4. Final design	2 files
5. Project initiation	25 files
6. Project management documentation	21 files
7. Personal observations	Diary

Different sources are used to identify the conceptual, undecided items (based on the CK-theory discussed in 4.1.2) in the design and to describe the effort related to the conceptual design in the project. The conceptual items in the design are identified using the final design, supported with the interview and personal observations from the researcher/practitioner (4.2.1). The project management and project initiation documentation provide insight in the timeframe of the development. The design documentation shows the progression of the design and the evaluation. The progression of the design is linked to the observations and project related emails to identify who was involved in the different stages of the design determining when and how conceptual items of the design are developed (4.2.2).

4.2.1 Identifying conceptual items in the design

The design of the SWind1000 (figure 4-4) is based on USoS's SOC5000. The SOC5000 is a dynamically positioned, heavy lift crane vessel with the aim to construct and maintain offshore surface or subsea structures. The vessel is equipped with a 5000 tons mast crane (Ulstein Sea of Solutions, 2011). The SWind1000 and the SOC5000 share the overall layout, hull form, propulsion system, marine systems and thruster layout (figure 4-13). The mission equipment of the SWind1000 is based on another project developed during a cooperation between USoS and UIES: the equipment on the available deck area on the SOC5000 included skidding arrangements and pile handling systems.

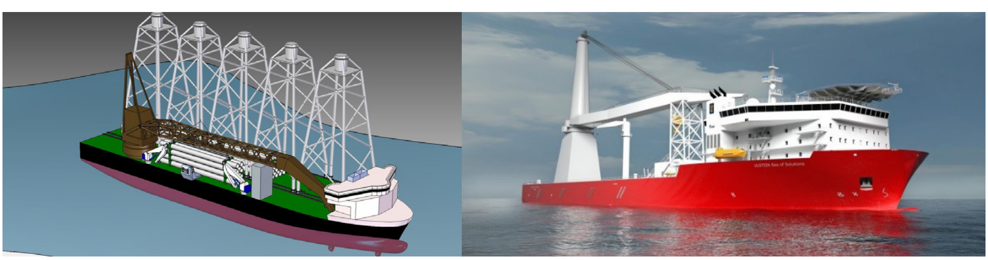


Figure 4-13. Swind1000 design (left) compared to the SOC5000 design (right)

The vessel is developed for the offshore wind installation industry (existing business case) and is based on the SOC5000 layout (existing ship design). The vessel includes a different systems (for example hull form, marine and propulsion systems), based on mostly existing components such as thrusters, accommodation, hull, and marine systems.

The SOC5000 design was modified to comply with the requirements of the client: the width was increased from 46.2 meters to 48 meters, the thruster layout was modified and the accommodation size was reduced to comply with the clients requirements related to DP capability, deck and crew size. Furthermore, the lift capacity of the main crane was reduced, while simultaneously increasing outreach. The majority of changes to the design concentrated on scaling and balancing the existing ship design (the layout) based on an existing set of systems with known components. To improve the capability of the vessel, the project included several new developments: a new rack to store and handle piles, a new crane to improve operation capability and a new midship cross-section. These newly developed components are undecided (or conceptual) in the early stages of the design, with considerable influence on the systems they are part of: the mission systems to install jackets and monopiles and the overall watertight subdivision, which implement these new developments. Figure 4-14 illustrates the systems and components in the design which are undecided or conceptual as defined in the CK-theory in the early stages of the design process; components and systems where design effort was required.

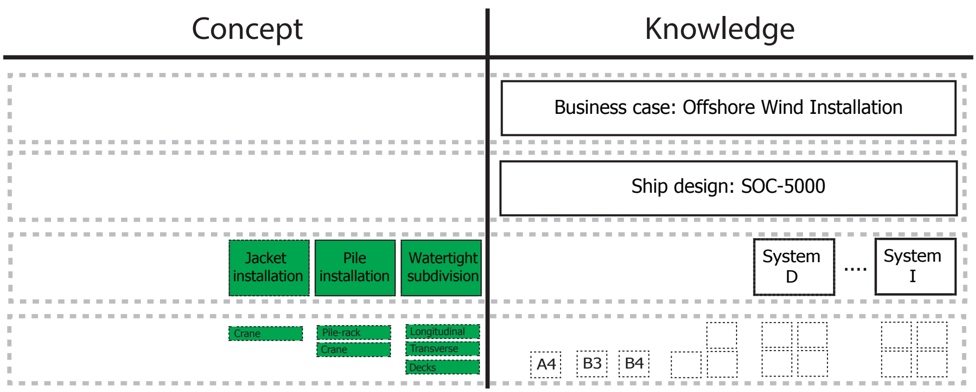


Figure 4-14. Identifying undecided objects in the early stages of the Swind1000 development (green)

4.2.2 Describing the development related to the conceptual objects

The effort in this project concentrates on the undecided (conceptual) objects discussed in the previous section, summarized from the case study report. Development of the conceptual elements was part of three out of four phases in the project. The fourth and final stage of the project (documentation) did not contain any activities related to the conceptual components and systems and is therefore not discussed in this subsection.

1. **Project initiation:** The project effectively started during a preliminary meeting between USoS, UIES and the client. During this meeting USoS suggested to compare the client's initial design with the SOC5000 design. Both documentation sets were reviewed and compared, resulting in a proposal from USoS to develop a new vessel based on the existing SOC5000, as it was more suited to the client's business case.

During these initial phases, although officially not part of the project, a wide range of decisions are made. During the project initiation the business case is set by the client, the SOC5000 is selected and system boundaries are defined based on the available design, complemented with deck equipment available from the UIES portfolio. These decisions are supported by both the client and technology partners, as became clear in later stages, however, these decisions were not documented.

2. **Initial design phases:** This phase started when the contract was signed and an initial basis of design was developed. During the initial phases, two developments were presented to the client: The first aimed to reduce the size of the vessel by modifying the overall layout. The original layout as defined in the previous phase was accepted by both the client and the involved technology partners. Furthermore, the client wanted to avoid a vessel that was only developed for a single market. The second development focussed the midship section to improve both watertight subdivision and operational performance. This was accepted and implemented in the vessel design.

3. **Development:** During this phase both the mission equipment (UIES) and the ship design (USoS) developed in parallel.
   a. **USoS:** The work done at USoS concentrated on modifying the vessel to comply with requirements of the client. This process, often called balancing or consolidation concentrates on selecting and scaling components to comply with the client's requirements related to operational performance and safety. In this project, these activities concentrated on evaluating and modifying the Dynamic Positioning (DP) layout and thrusters, the anti-heeling system and the new crane. The crane was based on an existing design but contained considerable modifications. Both the DP layout, the thrusters and anti-heeling system are based on existing solutions.
   b. **UIES:** The work by UIES on the deck equipment was based on an initial 'exploration memo': a memo based on previous projects. Based on the requirements of the client two components are redeveloped: the crane and the available pile rack system required considerable development. Both components are developed in more detail to ensure the validity of the designs. The remaining mission equipment, including skidding of jackets, lift systems and pile upending systems were based on existing concepts with only minor modifications.

The developments conducted during this phase resulted in a design that showed promise for this particular client. Both the design and the results from the evaluation were documented and sent to the client, marking the end of the project.

4.2.3 Summarizing creative effort in SWind1000 development

There are few conceptual or undecided propositions in the design. The creative developments concentrate on individual components, developed within an existing hierarchical structure. The newly developed components modify and influence the systems they are a part of, but have limited impact beyond changes to the system. The business case and ship layout are based on existing solutions. Subsequent stages concentrate on the conceptual development of the components and their effect on the involved systems. At this stage, both the respective system design and component designs were conceptual, and developed in parallel by both UIES and USoS. During different design review meetings the impact of new (conceptual) components is evaluated, switching between the concepts at both the system level and component level. Based on these developments new knowledge was generated. This process is visualized in figure 4-15, in dark blue.

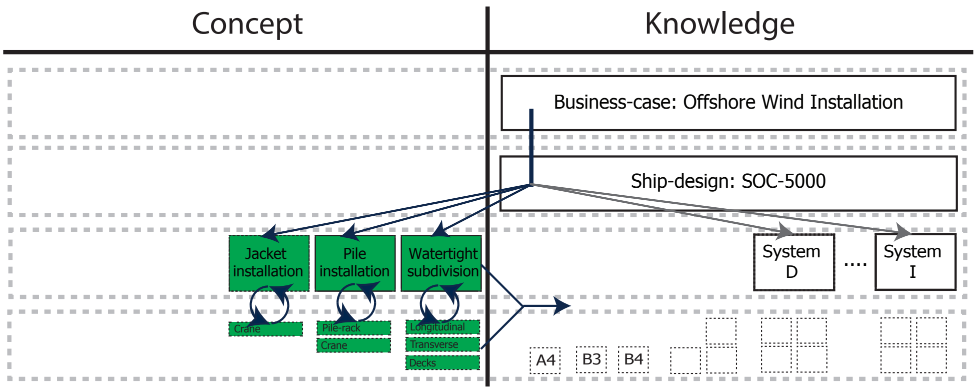


Figure 4-15. Representation of the design effort, C1

The different stages in this case study resemble some of the design strategies described in chapter 3: The initial stage of this project resembles the observations made in decision based design (3.2.3). The designer is described as a decision-maker, making decisions related to the business case, vessel design and system boundaries. The subsequent stages focus on the existing systems (figure 4-15, in blue) and can be described with a spiral-type approach; an iterative approach focussed on consolidation, optimization and balancing of the parameters in each system based on an existing solution. The impact of the conceptual or undecided systems and components was limited during this project. The way the conceptual systems and components were developed, in parallel and in a close collaboration between UIES and USoS could not be described with available theory.

4.3 C2: Greenstream

The development of the inland shipping tanker Greenstream started in the summer of 2009 at Peters Shipyard. The yard prior to this project primarily involved in the production of coastal dry cargo vessels. This project started to diversify their portfolio and increase their client base. To justify the relative high cost of production in Western Europe, the yard looked at a vessel in which they had added value, selecting a 100%-LNG (Liquid Natural Gas) powered inland shipping barge, the first worldwide.

The vessel was developed with a wide range of technology partners, potential clients, naval architects and equipment manufacturers. The development started in the summer of 2009 and finished approximately January 2011. During the subsequent phases the design was consolidated and improved. Production started in May 2012, the first vessel (of 2) was delivered in April 2013. The early design was developed by a small team: a project manager, naval architect and mechanical engineer, when necessary supported by technology partners.

The case is based on a dataset which includes interviews, design documentation, physical objects and publicly available information such as press releases and websites; all summarized in table 4-3. In this case study there was limited access to design documentation and no direct observations, but multiple interviews were conducted to strengthen the dataset. The documentation is stored in a separate database to support retrieval in a later stage.

Table 4-3. Dataset, case C2, Greenstream

Type	Amount
1. Interviews	3 interviews, 3h, 4m, 20s
2. Design Documentation	3 files
3. Physical Objects	3 files
4. Press Releases	2 files
5. Website	4 files

Different sources have been applied to identify the conceptual, undecided items in the Greenstream design and to describe the design effort in the project. The conceptual items in the vessel are identified using the physical objects and the press releases (4.3.1). The interviews, the limited design documentation and information from the websites provided insight in the development (4.3.2).

4.3.1 Identifying conceptual items in the design

The Greenstream currently operates in a time charter, transporting mineral oil and other chemicals, an existing business case, similar to other inland shipping vessels. The design of the Greenstream (figure 4-16) was not based on a previous designed vessel; the involved employees of Peters did not have any experience in developing inland ships.

Figure 4-16. The Greenstream: The first 100%, LNG-powered inland shipping vessel

Within the industry, the vessel was described as a considerable innovation; the LNG-propulsion system, the construction of the hull and the overall layout of the vessel with the propulsion system aft, (including LNG tanks and containerized generator sets) and the accommodation forward were all considerable changes for the industry (KNVTS, 2013). The development concentrated on the overall layout of the vessel, the structural layout and the propulsion system, although newly developed the propulsion system and structure were based on existing components: thrusters, engines, tanks, structural details. The remainder of the vessel was based on existing systems and components such as cargo handling equipment and bridge layout (figure 4-17).

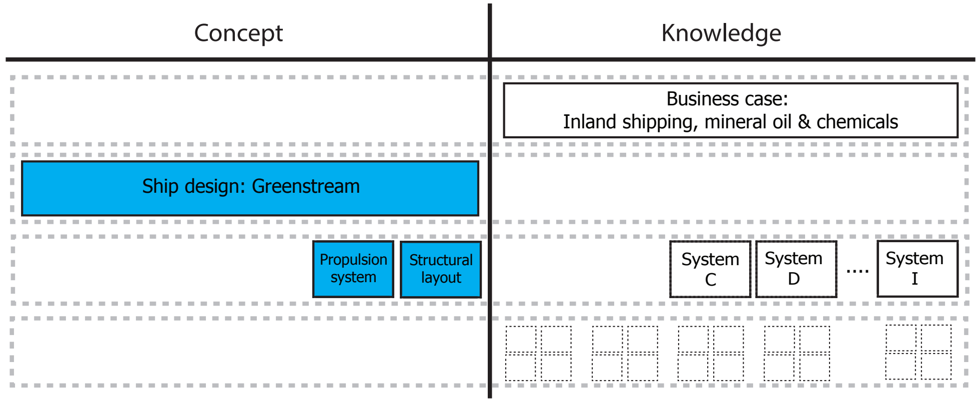


Figure 4-17. Identifying undecided objects in the early stages of the Greenstream development (blue)

4.3.2 Describing the development related to the conceptual objects

The effort concentrates on the undecided (conceptual) objects identified in the previous section, and summarized from the case study report. Activities related to the conceptual elements are identified in 5 stages. The final stage of the project, construction and operation, does not contain any activities related to the conceptual developments and are not relevant to the case as reported here.

1. **Project initiation:** The project was initiated by the Peters shipyard to diversify their portfolio, developing a new vessel in which the yard had added value. The initial draft was developed by a small project team, which included a project manager, naval architect and a mechanical engineer. The team, supported by the management selected and drafted the first sketches of an inland shipping tanker. According to the interviews, the initial drafts already included an LNG propulsion system but not the overall layout, although these sketches are not available to the researcher.

2. **Early developments:** The initial drafts developed further in close collaboration with other naval architects. During this phase the characteristic layout of the vessel was developed with the LNG propulsion aft, bridge and accommodation forward and a conventional tanker body in between. The propulsion system was developed with partners involved in the design of LNG-tanks and gas-driven generators. Each technology partner focussed on their specific components, with minor modifications to make them suitable for operation in a marine environment. The integration remained in the hands of Peters, who developed, what they referred to as a mini-bestek: a description of the selected concepts and solutions. During the end of the concept development the vessel incorporated the LNG-propulsion system and the overall layout.

3. **Client involvement:** After the early development phase a potential client and operator started to get involved in the development. Both provided specific knowledge on the

planned operation of the vessel. To communicate the current design 3D drawings were developed to make it possible to review the design, especially the operational features. The operator was particularly involved in increasing the cargo tank size in combination with the 'IJsselhuid': a novel structural layout of the vessel. The remaining changes were minor: changing bollards, spill-edges etc.

4. **Testing:** After the concept was largely finalized the design was tested to reduce risks related to the structure (testing the IJsselhuid design with Finite Element Analyses) and the LNG-propulsion system (performing a HAZID (Hazard Identification)) analysis in collaboration with the classification society). Furthermore the design was tested in a towing tank to determine resistance. At the request of the client additional tests were done to evaluate the consequences of low quality gas on the engine. At this stage, the legislative procedure started together with client, operator and the Dutch government to get dispensation for the LNG engines. Dispensation was only received in the summer of 2012, after construction already started.

5. **Consolidation:** After testing and before construction the design was further consolidated and the engineering was finalized. Dispensation was not provided yet, but based on the results from the testing phases construction of the vessel started.

4.3.3 Summarizing creative effort in the Greenstream development

New concepts developed during different stages of the project: the LNG propulsion system was developed an early stage, in parallel with the overall layout. The propulsion system had considerable impact on the overall layout of the design. In later stages, the overall layout evolved towards the current ship design, while the propulsion system was developed further in collaboration with companies specializing in parts of the LNG propulsion system. The implementation of the IJsselhuid, a new structural layout, made it possible to increase fuel tank size, reducing the amount of tanks from 10 to 6, increasing the operational performance of the vessel. The LNG propulsion system and the structural layout had considerable influence on the layout of the vessel. Still, they were based on existing components with minor modifications.

The design of the overall layout and the two key systems happened in parallel and with considerable influence on each other. These developments cannot be described with design processes in chapter 3. Somehow, the project allowed for alternating development of concepts by naval architects and the different technology partners. This is not consistent with point based design approaches discussed in section 3.2, where a framework is defined by the layout of the ship, and no changes to this concept are made. Nor with the top-down approach from Systems Engineering (3.3.2) or the development on a single level of decomposition such as system based design. The approach appears to have both top-down and bottom-up influence simultaneously, while developing two levels of decomposition in parallel, an effect which is not described before.

During the development of the overall layout, the structural layout and the LNG propulsion system involved the shipyard, multiple technology partners, potential clients and operators. The meetings, communication and discussions between these actors was not trivial, but played an important role to allow these solutions in multiple levels of decomposition to coevolve, moving into the concept space and eventually consolidating into the knowledge space. The creative effort during the design process is summarized in figure 4-18: The vessel is developed for an existing business case, but implemented both a new overall layout and two new systems. The remainder of the systems were based on existing, known solutions. There was a more complex interaction between the conceptual layout and these two new systems, which cannot be described with existing theory; although the systems were based on existing components.

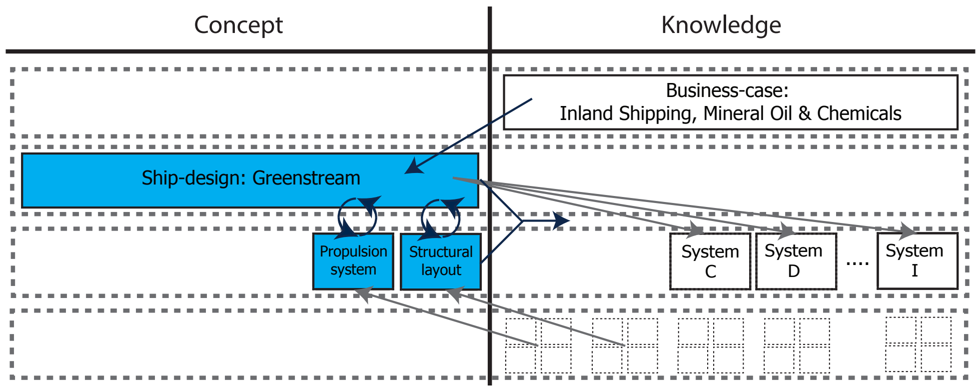


Figure 4-18. Representation of the design effort, C2

4.4 C3: Bourbon Orca

The Bourbon Orca has been developed during two projects initiated separately: the development of the safe anchor handling system (SAHS) in collaboration with Ulstein Design & Solutions (UDS), an equipment manufacturer and the eventual client and the development of a new medium-sized anchor handling tug supply (AHTS) vessel for the same client, as they searched for an innovative vessel to enter into this market. Although UDS and the equipment manufacturer had been working together in other, similar projects, the vessel was not based on a previous design. The project was developed and built in a short timeframe, the overall project time was approximately 2 years from project initiation to delivery of the vessel. The initial development of the vessel, before detailed engineering started, included approximately 7 months from initiation to delivery of the design.

The case description provided here is based on an extensive dataset including interviews, internal e-mails from UDS, patents, the eventual design, press releases and the design documentation, summarized in table 4-4. The vessel was developed and built by the Ulstein Group, which made it possible for me to access the design data. The documentation is stored to support retrieval when necessary.

The conceptual items in the design are identified using the final design, complemented with the patents and the press releases. The design effort related to the conceptual elements is identified using the design documentation illustrated with the interviews and the internal e-mails from UDS (table 4-4). The Bourbon Orca was delivered on the

28th of June, 2006 and is still in operation for the original owner. The vessel has been covered in a wide range of publications and won several awards, including the Ship of the year 2006 award (Skipsrevyen, 2011). The project was selected when reviewing innovative designs developed by the Ulstein Group.

Table 4-4. Dataset, case C3, Bourbon Orca

Type	Amount
1. Interviews	4 interviews, 2h, 5m, 24s,
2. Communication within UDS	12 e-mails
3. Patents	7 files
4. Physical Objects	6 files
5. Press Releases	5 files
6. Concept Design Folder	663 files
7. Ship production folder	518 files

4.4.1 Identifying conceptual items in the design

The design of the Bourbon Orca (figure 4-6) was not based on a design from the UDS portfolio but was an entirely new design; a new concept. The vessel was deemed a considerable innovation in anchor handling because of the overall layout and three major innovations: The X-bow®, an inverted bow which reduces accelerations, noise and vibrations, the SAHS (Safe Anchor Handling System), which includes the new anchor handling ramp, movable towing pins and cargo rail cranes, and the Diesel Electric propulsion system. Such a propulsion system has not been applied in such powerful anchor handling vessels because of costs and size considerations (Ulstein, 2006).

The vessel operates as a medium-sized anchor handling, tug and supply vessel in the Bourbon Offshore fleet, an existing business case at the start of the project. Both the ship design and the three innovative systems are conceptual in the early stages of the design process, the remaining systems are based on existing solutions. Although the hull, propulsion system and anchor handling system were innovative, the systems were based on existing components. The conceptual elements in the early stage of developing the Bourbon Orca are visualized in figure 4-19 in purple.

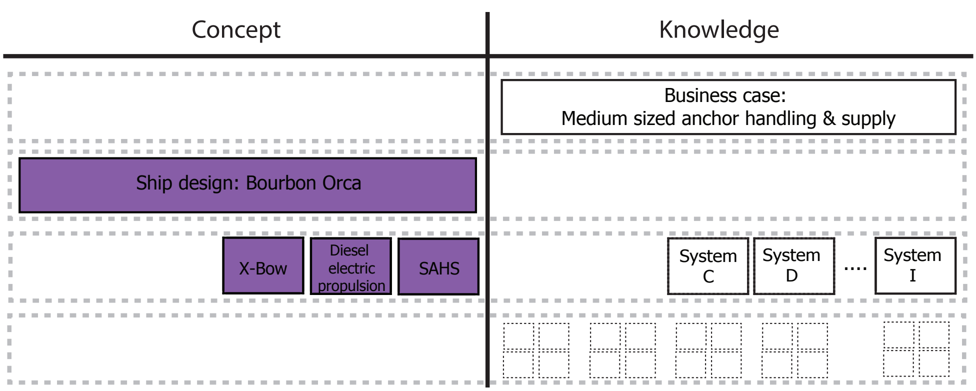


Figure 4-19. Identifying undecided objects in the early stages of the Bourbon Orca development (purple)

4.4.2 Describing the development related to the conceptual objects

This section concentrates on the development of the conceptual objects identified in the previous section. The effort related to the conceptual elements is identified during the first 4 stages, the final two stages concentrate on the realization of the vessel, not on the development of these concepts and are therefore not discussed.

1. **Project Initiation:** The development of the Bourbon Orca was originally part of two projects: the future ship owner aimed to increase their presence in the anchor handling market and initiated these two projects. The development of the Safe Anchor Handling System (SAHS) is discussed first, the development of a new vessel discussed afterwards. Both projects merged into the Bourbon Orca, discussed in more detail in the end of stage 2.
    a. **Deck equipment:** One of the major oil companies of Norway invited coalitions of equipment suppliers, naval architects and ship owners to apply for funding for the development of a new, safe anchor handling system, to reduce the number of accidents aboard anchor handling vessels; a necessary development as the operations on anchor handling vessel did not change in the last 20 years, even though the risks aboard these vessels were very high (Marinelog Magazine, 2004). UDS and the ship owner initially developed a design with another equipment supplier, presenting the results in august 2004 (Ulstein Group, 2004). After this cooperation UDS, the ship owner and another equipment supplier started to work together to reduce risks and optimize operations on the aft deck of anchor handlers, for example by reducing loads while handling heavy anchors or reducing risky manual operations.
    b. **Vessel development: I**n the early stages the vessel development concentrated on a conventional, medium-sized anchor handling vessel. The vessel did not include any of the three innovative systems discussed in 4.4.1, but was based on a conventional propulsion system, a single stern roller and a conventional bow. Although idea of this vessel was the starting point for the project of the ship owner and UDS, it was not developed further; the first General Arrangement sketches of the design of the future Bourbon Orca included the Diesel electric propulsion system and the initial representation of the SAHS system, effectively merging the two projects.

Parallel to the deck equipment and vessel development the first 3D renderings of the 'future OSV', or the AXoX, (figure 4-20) were developed at UDS, and subsequently published in the Ulstein Today (Ulstein Group, 2004) and the MarineLOG magazine (Marinelog Magazine, 2004). This development was not part of the Bourbon Orca at this stage of the project, however, in a later stage the ship owner saw these sketches and requested to implement the hull form in the Bourbon Orca design.

2. **Development**: Between August and December 2004 the initial design was developed further; the documentation remained limited, but drawings showed an integration of the DE propulsion system and the deck equipment. The development of both are discussed in the sections below. The final paragraph provides some feedback on the integration of both developments.

Figure 4-20. Ulstein AXoX, as published by MarineLog Magazine (Ulstein Group, 2004)

a. **Deck equipment:** The deck equipment is developed based on operational input from the ship owner, identifying risk-heavy operations. In later stages, they provided feedback on the commercial application of the design. UDS was involved to integrate the deck equipment, while the equipment supplier developed initial conceptual ideas further, evaluating technical and physical validity. At this stage few constraints played a role; new designs are developed and reviewed quickly based on short meetings and considerable communication between the involved partners.

b. **Vessel development:** The drawings of the design (at this stage called the "A104") were developed by UDS to include the DE-propulsion system (a first for this type of vessels) and the initial sketches of the SAHS (Safe Anchor Handling System). The vessel design was not finalized based on this concept, but the design continuously changed to incorporate the most recent developments in the (diesel electric) propulsion system and the deck equipment. One example was the implementation of large azimuthing thrusters, which resulted in modified aft hull lines.

At this stage of the project, the project teams extensively used the short communication lines between the 3 technology partners, with the three companies located within a radius of 40 km, making it possible to have ad-hoc meetings and discuss recent developments. This played an important role in the development of the Bourbon Orca.

c. **Integration:** The development of the two projects began to intertwine quickly, with the integration considered a joint effort by the equipment supplier and UDS. Both the deck equipment and the overall layout was adaptable, accommodating change from either side while the solutions were developed. For example the changes to the aft ramp, fully incorporated in the ship's hull lines. Solutions were selected based on the ship owner's input, aiming to improve functionality and/or performance. The developments were done in close cooperation and with mutual, open access to all design information.

3. **X-Bow® implementation***:* During the early stages of the project the initial 3D renderings of the Ulstein AXoX (figure 4-20) were introduced to the client. This draft of the X-bow® was only an artist impression, based on the experience of one of the UDS employees. The client picked up these drafts, as they liked the modern appeal of the design. The X-Bow® hull design was developed in parallel with a normal bulbous bow vessel (figure 4-21). The X-bow® was model tested early February 2005.

The results of the tests were sufficient to continue development of the X-bow® and apply the new hull form in the Bourbon Orca. The planned tank tests with the vessel with a conventional hull were cancelled.

Figure 4-21. Status January 2005, both the conventional bow (left) and the X-bow® (right)

4. **Detailed Development:** Based on the tank tests the design, including the X-bow®, DE propulsion system and the SAHS was developed further. The vessel was delivered on June 26th, 2006, and was considered an innovation for the industry, going into service for the oil company proposing the development of the SAHS.

4.4.3 Summarizing creative effort in the Bourbon Orca development

The process of developing the conceptual elements during the Bourbon Orca development was similar to the developments in the second case: The overall ship and system designs were conceptual. In this project, the development of the overall layout, the propulsion system and the Safe Anchor Handling System (SHAS) developed in parallel, while the X-bow® was a later addition, influencing the layout of the ship again. The three systems had a considerable impact on the overall design; requiring a different perspective on the design; there was a strong influence of the systems on the overall layout and vice versa, although each system was based on existing components.

The development of the elements considered innovative in the Bourbon Orca (three systems and the overall layout) cannot be described with the design processes found in chapter 3. During the project, the design of the ship design was developed parallel with the different systems. This occurred in the initial phases, with the SAHS, the Diesel Electric propulsion and the ship design, but also in a later stage during the implementation of the X-bow®. Similar to case study 2, there appear to be both top-down and bottom-up influences occurring simultaneously; an effect between system and overall ship development that is not described in detail in the theoretical frameworks.

The creative effort during the development of the Bourbon Orca is summarized in figure 4-22: the vessel is developed from an existing business case, resulting in a new ship design developed in parallel with three innovative systems. Both the vessel and the innovative systems are based on existing solutions to complement the innovative developments. Similar to the case study C2, the interaction of the creative efforts to develop a coherent design between the system designs and the ship design cannot be described with the existing theory.

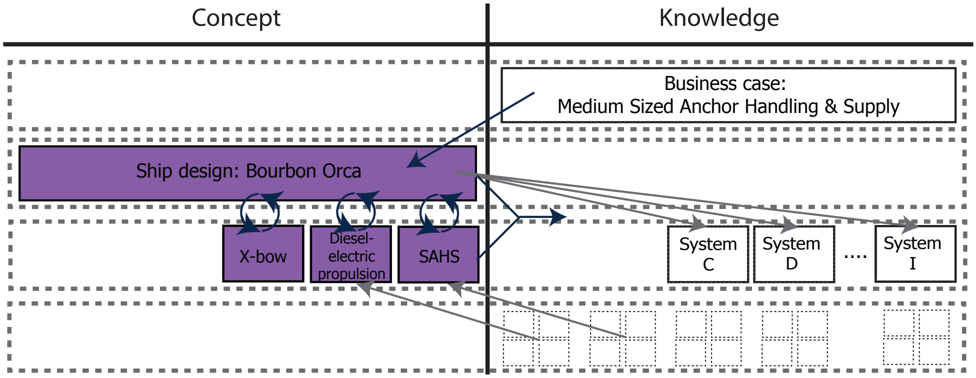


Figure 4-22. Representation of the design effort, C3

4.5 C4: Pioneering Spirit

The Pioneering Spirit was developed by Allseas as a vessel to commission and decommission large offshore platforms in a single lift. The vessel was initially based on merging two Very Large Crude Carriers (VLCC) into a catamaran hull (figure 4-23). The vessel is recently delivered from the DSME shipyard in South Korea, it is currently (early 2016) being outfitted in Rotterdam (figure 4-24). After delivery the vessel will enter into service for Allseas working on the removal of platforms in the Brent field (Eisenhammer, 2013) and several pipelay contracts (Offshore.NO, 2013).

Figure 4-23. Original design (Allseas, 2014)

Figure 4-24. Pioneering Spirit, (Allseas, 2014)

The project started in 1985, with initial publication of the design in approximately 1987. The overall project took approximately 30 years: a considerable effort by Allseas. The vessel was largely developed in-house, with the support of a broad set of technology partners. Allseas already announced the development of another new vessel with an increase to 72.000 tons lift capacity (the Pioneering Spirit is capable of lifting 48.000 tons) which should be operational in 2020.

Figure 4-25. Design of the larger single lift vessel (O'Cinneide, 2013)

The case described here is based on a limited dataset including an interview, scientific publications, patents and press releases & websites summarized in table 4-5. The documentation is stored to support retrieval when necessary.

Table 4-5. Dataset case C4, Pioneering Spirit

Type	Amount
1. Interview	1 interview, (49m57s)
2. Scientific Papers	6 files
3. Patents	6 files
4. Press Releases	13 files
5. Websites	4 files

The project is developed at Allseas and is still under construction making it difficult to evaluate a broader dataset at the time of this study. The concepts or undecidable propositions are identified using the patents, press releases and websites. The interview, the scientific papers and several press releases provide insight in the developments and when they took place.

4.5.1 Identifying conceptual items in the design

The Pioneering Spirit is described in several publications as one of the radical innovations in ship design and production of the last decade. The sheer size of the vessel, both in lifting and pipelay capacity and main dimensions captivate the public eye. The overall vessel (figure 4-26) and the (patented) lifting systems are new developments, developed from scratch.

Figure 4-26. 3D rendering of the Pioneering Spirit

The Pioneering Spirit applies a completely new approach to the decommissioning of large offshore platforms. The vessel sets new standards in the developing industry, although the vessel is based on existing components (quote 4-1). The design introduces a new business case: the installation and decommissioning of large offshore platforms in a single lift. The overall ship design is, both in size and layout are considerably different compared to other vessels in the industry. The design incorporates several new systems: developments with respect to structure, the jacket lift system, the topside lift system and albeit less than the others, the pipe lay system. The remaining systems and the components used in the Pioneering Spirit are all based on existing knowledge. The undecidable propositions (the concepts) at the start of this project are visualized in figure 4-27; in this particular project, this includes the business case, the overall ship design and several systems.

> *"You can generalize this statement. You can see that we are very innovative in the selected lift-systems, perhaps even in the hull-form, but especially in the lift-systems and the overall concept. On the component level it is more of a basic principle that we use off-the-shelf components: components that are already standard available, to minimize any extensive development."*

Quote 4-1. Naval architect, C4 (translated from Dutch)

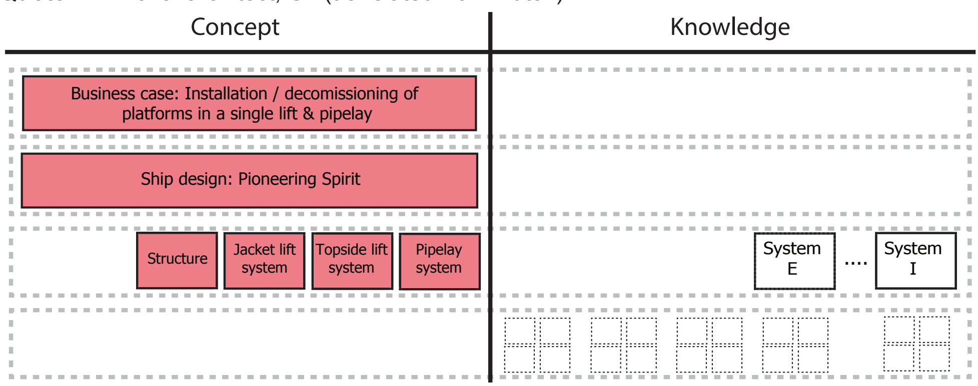


Figure 4-27. Identifying conceptual developments in the Pioneering Spirit (Red)

4.5.2 Describing the creative effort in ship design

Design effort is identified during all stages of the development, even throughout the detailed engineering and construction. Unlike the other case studies, the Pioneering Spirit was developed over a very long timeframe, making a detailed analysis of individual steps related to the conceptual developments in the design difficult. Some of the developments took place as early as 1985, followed by developments throughout the last 30 years. The design was developed by Allseas, making it difficult to access detailed information; in particular with respect to the earlier stages of the design. However, by identifying broader time steps it is still possible to make several observations, providing insight in the drivers of the conceptual activities. Six steps are discussed here, ranging from the projects initiation al through to the detailed design and construction:

1. **Project Initiation:** The project was initiated by the owner of Allseas, who wanted to combine two large VLCC (Very Large Crude Carriers) into a heavy lift vessel capable of installing large offshore platforms. During the early stages the project concentrated on the systems required for lifting, for example the active-control for lifting jackets and topsides, resulting in two patents.

2. **Oil Price Shock:** In the early 90's the oil price and second-hand prices of VLCCs increased dramatically because of the gulf war. The VLCC's are a key part in the design based on a conversion, making it infeasible to develop the design further at this stage. During this period the development of the Pioneering Spirit was stopped.

3. **Concepts development and review:** The decommissioning of the Brent Spar had considerable impact on the Pioneering Spirit project. In the aftermath of the events the OSPAR (The Convention for the Protection of the marine environment of the North East Atlantic) conventions require all offshore oil and gas facility to be disposed onshore after decommissioning. One of the designs presented to remove the Brent Spar was the Pioneering Spirit. The vessel was redesigned with a renewed focus on decommissioning instead of installation. During this period changes were made to the lifting system, which was redesigned based on mechanical principles instead of buoyancy principles.

4. **Conversion design development:** In subsequent stages development continued. In 1999 a daughter company (Excalibur Engineering) was established with the sole purpose of developing the Pioneering Spirit. Developments at Excalibur Engineering included a modification and relocation of the jacket lift system, using a portal based system over the side of the vessel. During this period the first client studies are done, which had a continuing influence on the development of the design.

5. **Newbuild design:** The previous developments were based on converting two VLCC's into a catamaran vessel. When in 2004 the oil price and second-hand price of VLCC's increased again it became less viable to convert two such vessels into a catamaran. In 2004 the Pioneering Spirit was redeveloped based on a newbuild design, resulting in a redesigned and repositioned accommodation, diesel-electric propulsion, improved DP capability, a new hull design, relocation of the jacket lift system. The majority of these changes are based on the client studies and progressive insights, but made possible when the choice was made for a newbuild design, because in the original design the layout of the two VLCC's, including their propulsion system, would have made these modifications impossible. During the development of the newbuild design the functionality of the vessel was further expanded with a pipelay solution, changing the business case. Allseas is a company originally involved in pipe laying, and the size and motion behaviour of this vessel made it possible to implement this new function. The first provisions were for a simple 'on-deck' solution but in subsequent phases the developments included an integrated large diameter and deep water system with considerable impact on the structure of the vessel, in particular in the crossbeams of the vessel.

6. **Detailed design & Construction:** Although it is not common to have major changes to the vessel during the detailed design and construction phases, it was the case in this project. During the construction of the vessel the decision was made to widen the vessel by 6.75 meters, to accommodate for potential client's requests.

4.5.3 Summarizing creative effort in Pioneering Spirit development

Throughout the 30 years of developing the Pioneering Spirit considerable changes are made to the design of the vessel. Although no detailed information about the different developments was available, the case study does show insight about how the design is developed over time. The project developed a new business case, a novel ship design and new systems; still, the remaining systems and the components were based on existing knowledge and existing designs.

The first step, the initial ship design concept, provided the input for the development of several systems: Systems that enabled the vessel to lift large platforms which resulted in two patents (Kaldenbach, 1990a; 1990b). The third step changed the business case of the vessel, resulting in new conceptual solutions for both the overall layout and several systems. The fourth step again concentrated on the development of the ship's systems, providing insight in the requirements for such a vessel. During the 5th timeframe, the decision was made to change from a conversion into a new-build design, which resulted in considerable system-developments and changes to the overall business case. Finally, during the construction the vessel was widened based on changes in the business case. The developments of the business case, the overall layout and the different systems were not singular events. Each development in either of these systems had an effect beyond their own boundaries; effects both upwards and downwards in the hierarchy. This interaction between these three levels of decomposition is visualized in figure 4-28.

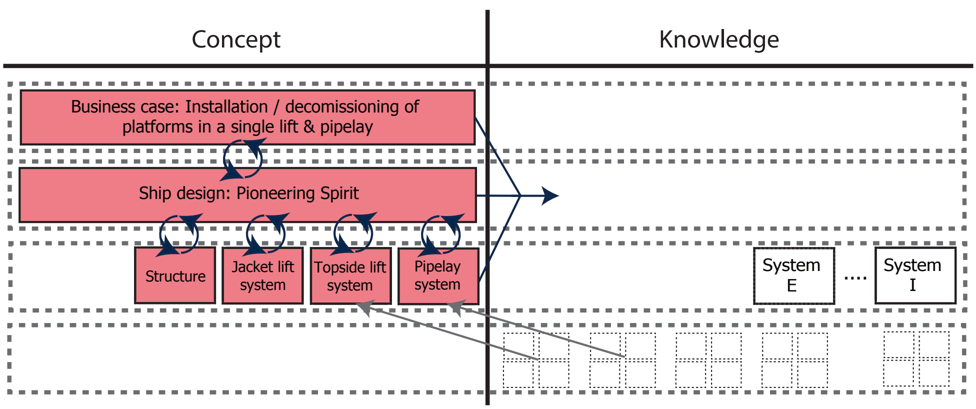


Figure 4-28. Representation of the design effort, C4

This approach appears to illustrate what happens during a 'white sheet of paper' design, resulting in a considerable effort by the involved actors, with major iterations over a prolonged period of time. Part of the design process: the interaction between the business case and the ship design could possibly be described with the requirement elucidation theory discussed in subsection 3.3.5. A theory which allows for the parallel development of both the business case (represented by the requirement owner) and the ship design (represented by the naval architect), a situation similar to the one observed in this case study. However, this case study lacks the richness to provide a detailed description of the activities during the interaction between these actors. There have been considerable activities related to the conceptual developments of the systems and the overall layout; activities that had considerable impact on each other that cannot be described with the available theory.

4.6 Cross-case observations

The chapter represents the observations done in 4 different cases, each focussed on developing a designated, complex vessel for a specific client, with different innovative content. This section draws cross-case conclusions based on the observations seen in the different projects.

4.6.1 Coevolution of different levels of decomposition

In each case, two or more levels of decomposition developed in parallel: In case C1 the system design and component design developed in parallel. In the cases C2 and C3 the system design and ship design developed in parallel, while continuously influencing each other beyond their own system boundaries. In the final case study, the business case, ship design and system design developed throughout the project. The focus in each case study, with respect to the conceptual, undecidable elements is visualized in figure 4-29.

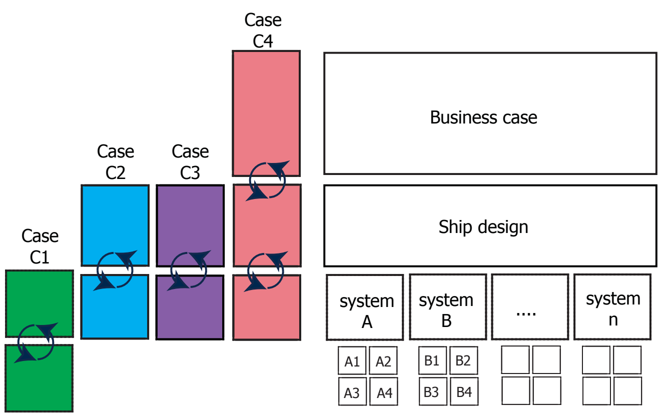


Figure 4-29. Visualizing the focus of creative effort in each project

During these parallel developments with mutual impact a form of technical coevolution (defined as the influence of closely associated species on each other in their evolution (Oxford University Press, 2015)) occurred. During these coevolving solutions considerable social interaction occurred between the involved actors as different actors were responsible for different tasks: often in face-to-face meetings, telephone conferences, e-mails and other ways of communication.

The available ship design theories do not describe this process of coevolving technical solutions on multiple levels of decomposition, nor do they discuss the interaction, both technical and social in much detail. Concurrent Engineering as applied by Mistree and Gale (Mistree, et al., 1990; Gale, 2003) appears to be the closest in describing such effects, although coevolution occurs during the conceptual stages and therefore appear to more akin to ‘concurrent design’, instead of concurrent engineering, as opposed to later stages, where an solution is further developed, balanced and optimized applying concurrent engineering principles. Still, the case studies C1 and C4 can be described with the available theory: the design in case C1 can be described using the decision-based design and the design spiral and the design in case C4 with the work on requirement elucidation and ‘clean sheet of paper’ design.

Still, even though parts of the design process in case C1 and C4 could be described the coevolution of different levels of decomposition and the resulting social and technical interaction is not. This is even more evident in cases C2 and C3, where the ship design and several systems coevolved from conceptual designs into physical objects. The social interaction between the involved actors at different levels of decomposition seems to play an important role during the ship design process but has rarely been explored in ship design literature, making it an interesting topic for further research.

4.6.2 The current state of practice in ship design

Based on the observations from the four cases it appears that during innovative ship design solutions on two or more levels of decomposition coevolve; multiple levels of decomposition are conceptual at the same time: not sequentially but in parallel. Coevolution and the interaction between different actors involved in this development have an important but little understood role in innovative ship design.

The observations provide additional insight in the problem; the main objective of the institution of the problem. Chapter 5 explores the concepts of coevolution and technical and social interaction further with respect to the case studies discussed in this chapter, but complements this with (ship) design theory, a set of interviews and an additional reference case in order to determine a problem-solution. A working hypothesis based on a change in perspective, to improve the description of innovative ship design.

Chapter

5

Describing ship design

"Determination of the problem-solution: identifying a working hypothesis for further research"

In this chapter conclusions are drawn based on the observations in chapter 3 and 4, with the aim to identify challenges and determine potential solutions (figure 5-1).

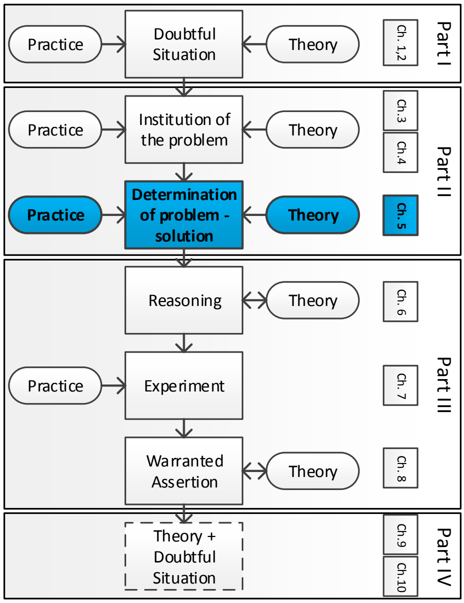


Figure 5-1. Overview of the research stages (equivalent to figure 2-6)

Section 5.1 summarizes the key observations from chapter 3 and 4. Section 5.2 and 5.3 explore potential solutions available in both theory (5.2) and practice (5.3). The final section (5.4) defines a combination of problem solution in the form of a constructive hypothesis, which is a starting point for further research (figure 5-2).

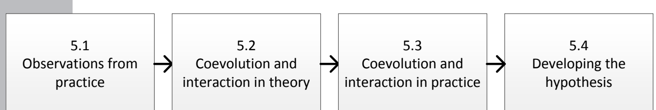


Figure 5-2. An overview of chapter 5

5.1 Observations from practice

The cross-case observations in chapter 4 introduce two terms expected to improve the description of innovative ship design: coevolution and interaction. These two terms are used to identify a new description of the observed parallel development of solutions on different levels of decomposition and the collaboration that takes place between different actors involved in these developments, visualized by figure 4-29. These two terms could be used to improve the description of innovative ship design, to refine them they are discussed in more detail in 5.1.1 and 5.1.2, before proposing a shift in perspective in describing ship design (5.1.3).

5.1.1 Defining coevolution

At the end of chapter 4, the term 'coevolution' is used to describe the parallel development at different levels of decomposition. During these developments the design on different levels of decomposition shifts from conceptual (where the initial sketches are made) into the knowledge space (where solutions are definitive) (Smulders, 2015). This process is facilitated by the close interaction between the actors involved in each level of decomposition (System X, System X-1) as shown in figure 5-3.

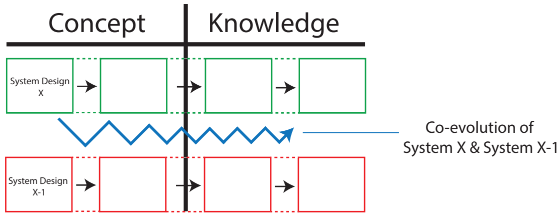


Figure 5-3. Coevolution between system X and system X+1

The cases in chapter 4 each show the parallel development on multiple levels of decomposition: in case C1, system developments and components were developed in parallel; in case C2 and C3 the ship design and system designs coevolved. In the final case study (C4) the business case, ship design and system designs coevolved throughout the 30 year development of the ship. The actors involved in the cases used different approaches in handling coevolving solutions. Based on the case studies four different approaches are observed applied to handle coevolving solutions:

In each project, existing elements are used to develop new solutions. In case C1, the ship design and many systems were selected from the available portfolio, in case C4, the innovative system designs were based on existing components such as thrusters and cylinders. In design theory, such an approach is often described as '*catalogue lookup*' (Gero, 1990). Such an approach provides the possibility to implement fully developed subsystems into a new system: This may lead to an innovative integration, but does not provide insight in the interaction between different levels of decomposition.

As introduced earlier, each case shows coevolving solutions on multiple levels of decomposition. Still, the way interaction occurred was not the same in each case. In the first and second case studies, the structural layout and the pile rack were developed within strict boundaries of a predefined decomposition: The system boundaries were strong and did not allow for influence beyond these boundaries other than previously defined, they were anchored by existing knowledge. In the second and third case several developments were allowed to influence the overall design beyond their own system boundaries: The LNG-propulsion system had considerable influence on the layout of the Greenstream and the Safe Anchor Handling System which influenced the overall ship design of the Bourbon Orca. During these projects the system boundaries at the different levels of decomposition changed continuously. The boundaries were not anchored by knowledge, but remained conceptual (undefined) for a long period of time before consensus was reached. For further use, these approaches to handling coevolving solutions are defined as developments in strong and weak boundaries.

The final case, the development of the Pioneering Spirit, was the only project based on developments on three levels of decomposition at the same time: innovative solutions were developed in system designs, the ship design and the business case. During the 30 year development input from each levels of decomposition resulted in major design iterations. The owner was fully committed in realizing the project, despite these major design iterations. Based on these observations, the developments on two levels of decomposition appear to be manageable, but more levels of decomposition could lead to major design iterations, requiring more time and effort.

Observations from theory and practice helped in refining the terminology of coevolution. In this thesis, coevolution concentrates on the development on multiple levels of decomposition, an expansion ship design, which in general concentrated on the development on a single level of decomposition. In practice, different approaches are observed to handle coevolving solutions: the catalogue lookup of standard components, developments in strong or weak system boundaries and developments on multiple levels of decomposition. Each approach requires a considerable amount of interaction between the involved actors. This interaction is discussed in more detail in the subsequent sections.

5.1.2 Defining interaction

Interaction appears to play a role in enabling coevolving solutions, based on the observations in chapter 4. The Oxford dictionary defines interaction as "*the reciprocal action or influence*" and "*the way in which matter, fields, and atomic and subatomic particles affect one another, e.g. through gravitation or electromagnetism*" (Oxford University Press, 2015). This research takes a holistic view of the interaction applied within the design team: it encompasses both the content (the technical dimension of interaction) and the way the information is transferred (the social dimension of interaction). In this approach, the interaction describes how the involved actors on different levels of decompositions influence and effect each other.

The different approaches to handle coevolving solutions (5.1.1) lead to different interaction between the involved actors. In some cases these interactions proved to be key in the development of innovative solutions. In case study C1, but also in other case studies, the interaction is reduced by selecting existing solutions. Still, when selecting existing solutions the designers have to be aware of the consequences of implementing these solutions in the ship design. In some cases, selecting specific engines or thrusters can have considerable impact beyond the original system boundaries. To evaluate such consequences specialized knowledge is required, knowledge that is not always available in the project team. Such interactions occurred in the first case, where Ulstein Idea Equipment Solutions provided specialist knowledge on existing solutions for windfarm installation, but also in case C4, where thruster manufacturers provided input for the thruster selection in the Dynamic Positioning system.

If system boundaries are strong, the interaction among actors can be limited. This is illustrated with the development of the crane in case study C1, as the different actors interacted through e-mail and conference calls, but required limited face-to-face contact. During the Bourbon Orca development the ship design and system designs where developed simultaneously, often supported by face-to-face meetings. In both case C2 and C3 the short communication lines but also the ease in which meetings were planned and the relative short distance to technology partners were mentioned during the as important factors in the success of the project, as discussed in step 2 of section 4.4.2. The discussions during the meetings ranged from objectives, system designs, and integration to performances of the vessel and individual systems: a complex set of interactions that allowed for changes to the system boundaries during the development of the project.

Because of the complexity and shear development time of case C4 there is limited insight in specific interactions between the different actors. Still, it is important to conclude that the involved partners and in particular the owner were fully committed, accepting large iterations in the ship design, business case and system designs.

What is clear from these cases is that creative design is not a purely technical phenomenon: while observing and discussing the interaction with the involved actors the value of face-to-face meetings, short communication lines and previous experiences were mentioned as a major influence on the developments. In literature such approaches are called sociotechnical (Kroes, et al., 2010): The convergence of technological and social insights in the creation, construction and use of artefacts (Radziwill, 2009). The interaction in this research contains both the social and technological challenges related to the communication and discussions that occur between actors involved in the developments at different levels of decomposition.

5.1.3 Shifting perspective in describing ship design

Both coevolution and interaction appear to play an important role in describing the design process of innovative, large and complex vessels. Based on these observations, a shift in perspective is proposed in describing ship design. From an original perspective describing an individual system toward a description which includes the development of two levels of decomposition in parallel (figure 5-4). This shift in perspective appears to be minor, but it has considerable consequences: the technical and social interaction an unwanted result of design, but become the basis of the design process. Subsequently, the decomposition of the vessel and how systems and components are harmonized over different levels becomes more and more important.

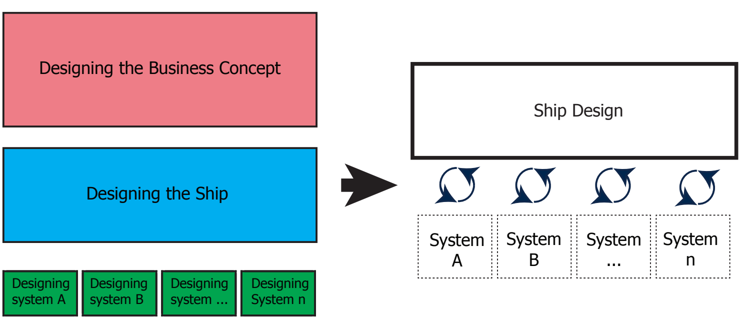


Figure 5-4. Shifting perspective in ship design: based on designing a ship, to designing the ship and systems in parallel

The decomposed perspective introduced in section 4.1 can potentially result in three sets of coevolving solutions within the scope of the ship designer: The business concept developed in parallel with the ship design, coevolving the ship and systems design, and coevolving system and component design.

When coevolving the business concept and the ship design both the client and the ship designer develop new, conceptual ideas and their interaction concentrates on the development of a new ship design, based on existing systems and components, integrated in a new business case. This process was observed in case C4, when the ship design was modified to suit the decommissioning business case. When coevolving the ship design and system design, the ship and system designers develop new, conceptual ideas. This interaction concentrates on the development of new systems, integrated in an innovative ship design with a set of objectives. Coevolution and interaction was for example visible in case study C2 and C3, where the Bourbon Orca and the X-Bow® coevolved. When coevolving the system design and the component design, system designers and component suppliers develop and implement new ideas. The interaction concentrates on the development of new components, integrated within new ship systems. In such projects, the ship designer often evaluates the consequences for the ship design, or develops naval architectural systems as a system designer. This was observed in the development of case C1, when developing new components for pile handling.

Such a shift in perspective in describing ship design could be beneficial to augment both practice and theory. The subsequent sections explore both theory (5.2) and practice (5.3) to explore questions raised by the proposed shift: how does communication between different actors influence the design? What kind of information is transferred? And how do different actors interact to enable the creative leap required for innovative design?

5.2 Coevolution and interaction in theory

Ship design (5.2.1), engineering design (5.2.2) and system engineering (5.2.3) literature is explored with respect to the newly defined terms of coevolution and interaction, before drawing conclusions (5.2.4).

5.2.1 Coevolution and interaction in ship design

Chapter 3 provided a review of the ship design literature concentrating on the creative aspects of each theory. Coevolution and interaction is only discussed by Andrews in requirement elucidation and system architecture (Andrews, 2004), (Andrews, 2012), mentioning the interaction with the client and other processes. Both concentrate on the coevolution of the requirement and the ship design; the interaction between the ship designer and the requirement owner. It allows both the requirements (based on the naval "mission") and the ship design to evolve simultaneously. System architecture also identifies the interaction with the client, including the conceptual and creativity in the design process. The foundations of systems architecture appear as a better fit for describing ship design than system engineering (discussed in 5.2.3) (Andrews, 2012), although this has not been evaluated in ship design at this stage.

5.2.2 Coevolution and interaction in engineering design

The engineering design discipline (as taught by Industrial Design Engineering at the Delft University of Technology) concentrates on the design of consumer products for a wide range of users. A large portion of the work done in this field concentrates on the human – product / user – object interaction, or the interaction of the design with a group of consumers (e.g. (Desmet, et al., 2001)).

The field of engineering design research is very broad, it discusses decision making in design (e.g. (Lewis, et al., 2006)), the role of stakeholders in the design process (e.g. (Vink, et al., 2008)), front-end innovation (e.g. (Koen, et al., 2001)), (virtual) prototyping (e.g. (Dimitrov, et al., 2007), innovation dispersion (e.g. (Bertuglia, et al., 1997)), social synchronisation with manufacturers for (mass) production (e.g. (Smulders, 2006)) and the social impact of the design (e.g. (Margolin & Margolin, 2002)). This wide range of research illustrates the diversity of the engineering design literature, this may prove useful in later stages, but it does not provide a direct answer for the challenges found in this research: It primarily concentrates on fast-moving consumer goods; goods that are produced in high-volume, with relative low complexity with a broad consumer base. Innovative design in these industries are often developed in-house by internal project teams (Stompff, 2012).

This field does provide an interesting insight into coevolution: In the engineering design literature the term of coevolution is applied to describe the development of the problem space and the solution space in parallel (Dorst & Cross, 2001), an approach initially defined by Maher et. al. (Maher, et al., 1996). This is not the same as the coevolution described in section 5.1, here coevolution discusses the parallel development of different system layers; in engineering-design coevolution describes the parallel development problem and solution in a single object. This problem-solution is developed from sketches (concept) into a more concrete solution (knowledge), as visualized in figure 5-5. The definition as applied by Dorst & Cross has not been applied to a system of systems with multiple levels of decomposition, where problem & solution on different levels of decomposition influence each other.

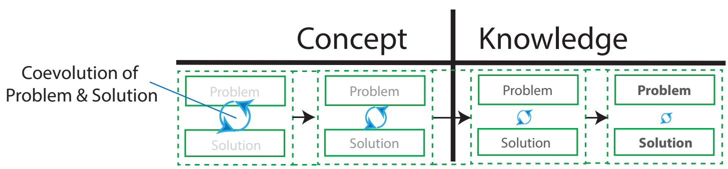


Figure 5-5. Coevolving problem - solution

Engineering design research provides an interesting knowledge base with respect to defining interaction and coevolution in design, still it does not appear to provide a ready-made answer to describe coevolving solutions on multiple levels of decomposition.

5.2.3 Coevolution and interaction in system engineering

The system engineering (SE) literature discussed in section 3.3.2 is developed for organizing and managing the development of large, complex structures over the entire life-cycle. The approach assumes an understood situation with complete frameworks among the various levels (Maier & Rechtin, 2000), based on the decomposition of an existing object. Originally, the approach does not allow for design feedback, although this has been incorporated in later versions of the theoretical framework (Andrews, 2012). The interaction between the different levels of decomposition usually defined based on 'requirements' and 'design feedback' (figure 5-6). This is similar to the observations in the cases, although it does not provide insight in what the content of both are.

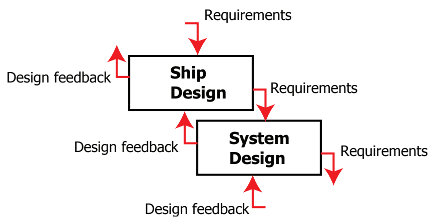


Figure 5-6. Interaction in system engineering: requirements and design feedback (Technical Board - INCOSE, 2004)

System Engineering provides a generic framework to manage the development of these large, complex vessels. This is a framework which includes breakdown structures, supports integrated product teams and kick-off meetings with all involved partners. System engineering still approaches the design of different levels of decomposition sequentially: the approach does not allow for coevolving solutions on different levels of decomposition with considerable social interaction among the actors representing these coevolving solutions.

5.2.4 Conclusions

Ship design, engineering design and system engineering literature provide some insight in describing innovative ship design by taking coevolving solutions and interactions into account. They do not provide a direct answer in how to manage and describe the technical and social content of the interaction caused by coevolving solutions in such large, complex and innovative solutions as ships.

Several theories identify coevolution in two levels of decomposition such as the work done on requirement elucidation (5.2.1), or recognize the coevolution of problem and solution within an object (5.2.2). Still, none provide a sufficiently description of interaction between multiple levels of decomposition and the social and technical interaction part of these developments.

5.3 Coevolution and interaction in practice

The available theory does not provide a direct answer to describe what happens during the coevolution and interaction in the design of large offshore vessels. In spite of this, practitioners already use different approaches to manage coevolution and interaction in their projects (5.1). The following section explores how practitioners manage and organize these coevolving solutions in more detail, first discussing an example from another industry, describing the development of an F1-car (box 5-1), before discussing how coevolution and interaction is managed in the four case studies. These observations are complemented with interviews with ship designers in the industry and an additional case to explore coevolution and interaction in practice before the conclusions are drawn.

Developments in Formula 1 racing

The following case uses the well-documented description of one of the most innovative designers in the Formula 1 – Gordon Murray –, based on a full review found in (Cross & Clayburn Cross, 1996). The first case study shows the approach Mr Murray took to reframe the problem; the second shows the potential of redefining context.

1. **Redefining system boundaries:** In 1981 the governing F1-organisation (FISA) strived to reduce cornering speeds in F1-cars to reduce G-forces for the drivers. To accomplish this, the FISA introduced a minimum ground clearance of 6 cm. Gordon Murray, as he had done previously, aimed to develop the fastest car for the Brabham team. However, to maintain cornering speed he needed sufficient downforce. This translated in a specific set of requirements: limited ground clearance in corners, increasing downforce but a minimum ground clearance when measured by the FISA. The suspension he developed was based on a hydro-pneumatic solution, activated by the aerodynamic form of the car. The solution was very successful and won the 1981 championship.
2. **Redefining context:** In the early 80's the Brabham team introduced a new race strategy which included the use of planned pit stops. During this period Mr. Murray was looking for opportunities to improve the performance of his car to gain an advantage during the race. Within this development, he looked at the car's context: the race or championship the team needs to win. Within this scope, the car is a single aspect (albeit an important one) but other parts include strategy, tires, the driver and the team organisation. Based on his observations Murray explored the idea of running the car with 50% fuel; in the existing framework the car would not finish because it would run out of fuel. By including other parts in the development (the pit stop and race strategy) Murray could evaluate and trade off the car's performance in this new context.

The 1981 F1 car developed by Gordon Murray (Switala, 2012)

The team of Gordon Murray was involved in a wide range of innovative solutions in Formula 1. In the two examples he uses a different approach. In the first he redefines system boundaries within the car, to comply with regulations and maintain downforce: looking for interaction between the car design and the systems. Within the second example he concentrates on the car's context: the race, redefining the required performance of the car supported with the other parts of the race.

Box 5-1. Developments in Formula 1 racing

5.3.1 The case studies

The observations in chapter 4 provided insight in the way coevolving solutions are managed in practice. Still the involved actors had different ways to handle the technical and social interactions. These approaches are derived from practice and documented to provide a basis for a theoretical description of interaction and coevolution, developed in chapter 6.

Developing innovative solutions does not only entail developing new concepts, but also includes the evaluation of the new concept. The performance of the new concept, especially within existing (or new) context, plays a role in accepting an innovation and developing it further. In many cases the evaluation of a new design requires specific knowledge, knowledge of similar complexity to the knowledge necessary to develop new solutions. In case C2 the classification society provided extensive knowledge in evaluating the LNG propulsion system, supporting the development of the FMEA (Failure mode and effects analysis).

The integration of innovative solutions plays an important role in determining the impact of the innovative solution. During the development of case study C3 the diesel electric propulsion system and the safe anchor handling system (SAHS) were several times reintegrated in the overall design to identify clashes and provide insight in the technical interaction within the overall design.

The example in box 5-1 and all the cases show that for innovative solutions the context (the circumstances in which the solution exists) plays an important role. First of all, the context influences the characteristics of the innovative solution. Furthermore, the innovative solutions (the SAHS, the X-Bow®, the LNG propulsion system, the hydro-pneumatic suspension) are part of their respective contexts (the Bourbon Orca, Greenstream tanker and the F1 car), but also influence the overall design.

It appears that concentrating on two levels of decomposition, leads to more manageable development project. The first three projects concentrated on two levels of decomposition (figure 4-29). The 4th case had concepts on 3 levels of decomposition (figure 4-27). These three levels of decomposition appeared to have a considerable impact on each other, resulting in major design iterations. Although the amount of cases is limited, it appears that limiting the amount of levels of decomposition could reduce the possibility of design iterations.

System boundaries have an influence on the development of innovative solutions: changing boundaries make it possible to redefine and cluster challenges and develop these challenges into innovative solutions, previously not considered. System boundaries are developed when system is developed into subsystems; a lower level of decomposition. Changing system boundaries as discussed in the example of the F1-car in box 5-1 and developing the LNG propulsion system. Although the initial setup of the system boundaries is important, maintaining flexibility and re-evaluating system boundaries occurred during the development of the SAHS: Boundaries continuously modified and changed, to accommodate development of both vessel and system.

These observations illustrate different elements of how coevolution, technical and social interaction are handled in practice. It provides an initial insight in developing a coherent description of coevolution and interaction. To expand on these observations and to create additional insight, different leaders of industry were interviewed in addition to the cases.

5.3.2 Interviews with leaders of industry

Different actors involved in innovative ship design were interviewed to increase the data beyond the available case studies and to complement the observations with additional information on how practice handles innovative designs. In some cases, these elements overlap with the observations in section 5.3.1, but to provide a full overview, all elements are discussed. The interviews were with people in a wide range of responsibilities, ranging from clients, managers and (ship) designers (table 5-1). The interviews were conducted in an open manner, discussing the role of innovation in ship design and how to develop innovative solutions within the industry.

Table 5-1. Interviews

Function	Company
1. Director technology development	Shipyard
2. Manager naval architecture	Oil and gas industry (2 interviews)
3. Manager engineering	Naval architecture in oil & gas industry
4. Consultant	Cruise industry
5. Manager	Naval architecture in Yachts
6. Concept design manager	Offshore mooring equipment and operations
7. Naval architect	Shipyard, cruise-vessels
8. Technical director	Engineering and naval architecture
9. Consultant	Oil & gas
10. Managing director technology	Naval architecture in coastal and oil & gas industry

The open nature of the interviews made it possible to get additional insight in the different mind-set on managing coevolving, innovative solutions. The interviews are transcripted and segments were compared and evaluated. These observations are grouped in sections, to illustrate the insight gained from the interviews:

During several interviews the relation between developing creative, innovative solutions and developing the scientific background supporting these innovations was discussed. The case studies show that in the development of innovative solutions special attention is given to evaluating these solutions, as a new development potentially changes the frame of reference of their respective industry. This was drawn even further when stated that science follows innovative solutions [interview (2)]. During the interviews several examples were provided such as the development of the steam engine, preceding the development of the 2^{nd} law of thermodynamics and the development of Tension Leg Platforms, preceding the research in Vortex Induced Vibrations. Still, there are also examples of innovations that stem from scientific research. Such as the development of the Axe Bow. In both cases, experts are necessary to evaluate the combination of new technologies [interview (4)].

Several of the naval architects and (project) managers illustrated the role of the general arrangement (GA) during the early stages of the design process [interview (4), (5), (7)]. They mentioned that the GA had a different role in an early stage compared to the later stages of the development; in some cases the GA was a tool that allowed for the flexible integration of systems in the design, in others it represented a final, established solution. To accommodate different roles, completely different tools were applied to communicate with the client. Some of these had a low level of detail, but were more flexible compared to AutoCAD drawings.

All interviewees, without exception, were convinced that the concept of the solution played an important role during the development. Even when the idea was not developed into a sketch or drawing it still played an important role as it was used as a mindmap or reference to discuss performance parameters or define requirements. In many cases the communication would benefit if this concept was made explicit [interview (10)]. This results in a difficult imbalance, because predefining a solution stifles innovation, as it is often accepted as the final solution and not as a flexible draft.

The majority of project managers were adamant in the acceptance of failure in innovation. Almost all knew and accepted that there were no guarantees when innovating, although there were different approaches to manage potential failures. One discussed the possibility to disconnect developing innovative solutions from the commercial track [interview (6)]. In the offshore industry risks related to innovation were calculated using a, to the offshore industry common, approach. The industry accounts for potential failure of innovations [interview (2)].

The social interaction with project specific content has been a returning aspect in all interviews as a major influence while innovating. The social interaction was improved by changing the office layout to increase proximity of important actors, removing doors from offices [interview (2)], improving communication skills to connect with different cultures [interview (3)] and discussing reviews with other team members, to share creative ideas [interview (7)]. The role of knowledge is more guiding and even though it can stifle innovation, product specific knowledge is considered absolutely necessary to direct the creative process [interview (6)]. This leads to programs to identify and recognize knowledge, especially in specialist fields such as offshore and naval [interview (1)]. Still, the interaction between knowledge and the selection of creative solutions is not easy to define. In early stages the amount of project specific knowledge is limited while it is necessary to take decisions, but generating new knowledge is often impossible within the confines of a conceptual design (science follows design) [interview (9)].

5.3.3 The current state of practice: a reference case

Based on the observations from chapter 3 and 4 an additional case study in practice was done to provide additional information with respect to coevolution and the technical and social part of interaction. The reference explored the development of the Ulstein LWI-vessel vessel: a light well intervention vessel. This section discusses how the reference case was developed, the design of the vessel and the observations related to the content (the technical aspects of the interaction) and the organisation of the interaction.

The development of the reference case: The Ulstein Light Well Intervention (LWI) design (figure 5-7) is developed by Ulstein Design & Solutions (UDS) for a project initiated by Statoil, early 2013. Statoil selected two companies to develop a vessel for light well intervention operations, the first concentrating on a column stabilized unit, the other concentrating on a ship shaped unit. UDS was selected based on their previous work and the concept they presented during the sales phase.

Figure 5-7. The resulting Ulstein LWI-design

The concept was designed in collaboration with a wide range of technology partners. Statoil contracted three well intervention equipment designers ('topside designers') and two Remote Operated Vehicle (ROV) designers to develop the mission equipment in collaboration with the naval architects. During the project, UDS was supported by two companies within the Ulstein Group (Ulstein International and the Ulstein shipyard), the classification society and a tank test facility involved in evaluating the operational behaviour of the vessel. The case study is based on the dataset summarized in table 5-2, stored for reference.

Table 5-2. Dataset, reference case: LWI-Vessel

Type	Amount
1. Interviews	4 interviews, 2h57m
2. Physical objects	5 files
3. Design documentation	5888 files
4. Project initiation documentation	3 files
5. Project management documentation	897 files

1. Interviews: After the final design report was delivered four interviews were conducted with the client's project manager and three members of the UDS project team. The interviews were conducted in an open manner to illustrate the different experiences related to the way the project was organized.
2. Physical objects: The design resulted in four different general arrangements: one more generic arrangement and three arrangements for each company involved in the topside (the mission equipment on deck) development. The arrangements complemented with the concept design report describe the result of the design process.
3. Design documentation: The design documentation contains all the documents and files that are part of the design project, including deliverables, calculations and communiqués.
4. Project initiation documentation: The project initiation documentation contains information from the sales phase: before the project officially started.
5. Project management documentation: The project management documentation identifies all the contracts, hours and budgets related to the project.

Development of the LWI-Vessel: The Ulstein LWI vessel was developed over a period of 24 weeks, from the kick-off meeting at the end of April 2013 to the delivery of the final feasibility report in early October 2013. The final stage, the after-care is not discussed in this section, as it included no further design steps. The stages are defined figure 5-8 and discussed in the subsequent paragraphs.

Figure 5-8. Development of the LWI-Vessel

During the sales phase, before the official kick-off in April, 2013, development already started. During these phases UDS developed a prefeasibility design as part of the selection procedure of Statoil. UDS presented a ship shaped solution, based on previously developed LWI vessels (figure 5-9), which included the X-bow® and an optimised aft ship (the later X-stern). In the initial phases, the Statoil requirements showed they were looking for a vessel with low costs (operational and capital expenses), but with an increased operability.

Figure 5-9. Proposed prefeasibility design, from the sales presentation

UDS was selected to develop the ship shaped solution and the project officially started with the kick-off meeting in April, 2013. At this stage of the project, UDS had to cooperate with two topside designers; who were involved in the development of the mission equipment on deck and two ROV (remote operated vehicles) designers, the third topside designer was added in a later stage. The project initiation was challenging, as the project required a more extensive organisational structure than their usual projects (quote 5-1).

> *"We had to make an organisation, but we weren't given any time to do that, it was a very difficult start of the project: I was serving both as a naval architect and the project manager; handling the organisation structure, planning etc."*

Quote 5-1. Naval architect, Ulstein LWI-vessel, UDS

The initial concept was developed based on the prefeasibility design (developed during the sales design), providing the topside and ROV designers with the first physical interfaces on deck. The technology partners and the naval architects started their project based on these initial concept developments. During these initial phases Statoil pushed for additional information to ensure that the project proceeded as planned (quote 5-2).

> *"As far I can remember, it took some time before we actually got drawings from them [the topside designers], but we were continuously pushed by the client. They wanted to see something from us; the first GA, the first hull, was therefore developed without much input from the topside vendors."*
>
> *"We didn't understand how UDS was working in the beginning, and that was a little bit frustrating; and we thought about when we should take action."*

Quote 5-2. First: project manager, Ulstein LWI-vessel, Ulstein International. second: project manager, Ulstein LWI-vessel, Statoil

The pressure from Statoil caused a challenging situation for UDS, as they were dependent on the information from the technology partners (the topside and ROV designers) to develop the design, which was not available at that stage of the project (quote 5-2). During the concept development (between mid-May and the end of June) UDS aimed to develop a single platform for all technology partners. However, the late delivery of the equipment and the limited constraints UDS wanted to pose on their technology partners quickly resulted in multiple designs to incorporate the developments of each partner. The topside and ROV designers continued to develop their respective systems based on the initial interface provided by the prefeasibility design.

Statoil defined early in the project that they were looking for a design with a high operability and low costs. To evaluate the operability of the overall design a research institute got involved to test the design on seakeeping performance. Only a limited amount of data was available during the tests, making it necessary to test a generic concept, instead of the specific designs developed with each technology partner (quote 5-3).

> *"We tried to say to both the client and the two topside vendors that we needed to finalize the hull-design, the placement of the moon pools and the sizing, to move forward with the operability analysis and an additional study."*

Quote 5-3. Project manager, Ulstein LWI-vessel, Ulstein International

The initial stages did not go smoothly (quote 5-4), so based on their experiences during these phases UDS decided to restructure the project at end of June. For this, UDS developed a new project plan which included delivery dates for all technology partners. This new plan and schedule was accepted by Statoil, on the condition that a third topside designer was integrated in the design.

> *"I think the client's project manager used a strategy of pushing, intimidating and 'scaring' us to do what he wanted us to do: if he said we would jump, then we jumped, it was almost a panic at the beginning; we did what he said, but that was not necessarily the way to move forward early in the project."*

Quote 5-4. Project manager, Ulstein LWI-vessel, Ulstein International

The third topside designer was involved in the project from early July, 2013 but had limited design space. The ship design had been developed in more detail as a large part of the design study was already finalized. This topside designer had a slightly different approach, as they developed a topside based on the available information, but with limited to no feedback of the naval architects. During the final stages of the project, the focus shifted from conceptual developments to the evaluation and documentation of the final design. UDS planned to review the deliveries of the different technology partners, but as delivery of documentation did not always go as planned this evaluation was only limited. The project concluded with a workshop with the Statoil project team and several potential operators of the vessel.

Evaluation of the technical results and the organization: Based on the finished project four interviews were conducted to identify the experiences of different actors in the project. The interviews provided feedback on the actual design, design strategy and the social interaction. The following paragraphs discuss these observations, split between the technical and organisational subjects. During the interviews it became clear that Statoil aimed to develop a LWI-vessel with a focus on high operational capabilities and low costs. The design had to be realistic, without major or radical innovations (quote 5-5). The vessel incorporated the X-bow® and X-stern combination to improve operability in harsh conditions. Both the bow and stern were incorporated from the initial general arrangement, but why and how this was developed was unclear as opinions differed (quote 5-6).

> *"The client really wanted to have the drawings; they wanted a concept that had to be realistic; it had to be built within the timeframe that they set, so there couldn't be any crazy ideas that have not been tried before."*

Quote 5-5. Project manager, Ulstein LWI-vessel, Ulstein International

> *"I believe that the double X-bow [X-bow & X-stern] would not have been developed if we were not challenging them"*

Quote 5-6. Project manager, Ulstein LWI-vessel, Statoil

The innovative bow and stern had a considerable impact on the overall layout of the vessel implemented in the earliest versions of the design. Other innovative solutions such as the Ulstein Bridge, the ROV and topside layouts were incorporated within the physical boundaries defined in the initial concept. UDS was not always satisfied with these solutions, as topside designers did not integrate their solutions in the vessel but followed distinct boundaries (quote 5-7). Although integrating systems in the vessel could have resulted in a smaller ship. Statoil was satisfied with the improved operability and functionality, but the eventual cost of the vessel was too high to continue the project.

> *"One of the biggest disappointments was to get the topside vendors to understand that they were working on a ship, that they could utilize that ship: they wanted to draw a rectangle and put their equipment on a single deck."*

Quote 5-7. Project manager, Ulstein LWI-vessel, Statoil

This project followed a common approach in the ship design industry when a concept defined early in the project is modified to the client's requirements. UDS described this process as a set of skilled people working closely together (quote 5-8). The more extensive nature of this project, compared to projects usually done within UDS, made this project difficult to manage, because an extensive organisation was necessary to handle the complexity and the (technology) partners (quote 5-9).

> *"One of the first things we said to the client during the initial kick-off was that we didn't have a linear design process; it's very iterative, but it doesn't follow a line: It's a cloud of skilled people working closely together, and I think it ended up being correct."*

Quote 5-8. Project manager, Ulstein LWI-vessel, Ulstein International

> *"That was a big lesson learned: If you do these kinds of processes, you need an organisation to handle it and that should be available upfront, or else you will be losing to much valuable time."*

Quote 5-9. Project manager, Ulstein LWI-vessel, Statoil

The lack of a detailed process and challenges within the organisation caused considerable friction between the project teams of the client and UDS. The client continued to push for information to evaluate and review progress, although in some cases, UDS was not able to send this information at that stage of the project. UDS mentioned that they were not used to working with such a broad range of technology partners, as they are more used to working with a single, local vendor (quote 5-10). This was opposite to the opinion of Statoil, who mentioned that the structure with multiple partners, contracted by themselves, improved their influence on the eventual design (quote 5-11).

> *"The time-frame and having to work with many topside vendors was a big obstacle. If we could have worked with 1 topside vender; working closely, like we did with Bourbon Orca, we could work together for a good solution."*

Quote 5-10. Naval architect, Ulstein LWI-vessel, UDS

> *"I think that we would have less influence if we contracted one vendor, who subcontracted the others; we would have less influence on the solutions, on the outcome, and it might not be the optimum for the business-case."*

Quote 5-11. Project manager, Ulstein LWI-vessel, Statoil

One of the most interesting observations within this case are the consequences of the limited control on the conceptual design process, this does not only strain the relation with the client but results in a less controlled approach to innovation. Similar to the observations in case study C2 and C3 of chapter 4 the innovative elements 'happened', but were not part of a controlled process. Another observation concentrates on the interaction with the technology partners. The initial draft of the design provided technology partners (in this case the topside and ROV designers) with a necessary template and constraints, even though the naval architect was not happy when the developers remained within these constraints (quote 5-7).

5.3.4 Summarizing observations from practice

The observations from practice discussed in 5.3.1 and 5.3.2 provide insight how practice handles the sociotechnical process of coevolving solutions. The observations within this section concentrate either on the content (the technical dimension of interaction) or on the way the interaction occurs (the social dimension of the interaction). The observations from theory and practice are combined in 8 main observations: 6 related to the technical dimension of the interaction, two to the social dimension:

1. Evaluation: In the cases and the interviews the challenges of evaluating innovative solutions were mentioned. In all cases, specific knowledge is required to evaluate new solutions. In some cases this goes even further, as new scientific breakthroughs are required to evaluate innovative solutions. The development of new knowledge based on concepts requires a way of handling new solutions, including the evaluation of these solutions. This includes, when necessary, the development of specific knowledge enabling this evaluation.

2. Integration: The integration of new solutions plays an important role in the development of innovative ship designs. This is not a single step: actors continuously seek to integrate these solutions into the ship design; either to recognize clashes or to improve insight in the cohesion within the overall design. In the early stages of the design process, several companies therefore use different tools to accommodate this, such tools allow for a conceptual, undecided integration, without the necessity to fully develop the overall ship design.

3. Context matters: Both case studies and the example in box 5-1 show that to develop innovative systems, context plays an important role. The role of context is complex, it influences the characteristics of the system but the innovative solution itself is also a part of its respective context as it directly influences the system when changed. Both should be taken into account in the approach to handle innovative solutions.

4. Managing two levels of decomposition: The case studies and the example in box 5-1 show that to take a structured approach to innovative design, the design process can concentrate on coevolution on two levels of decomposition. Taking into account more levels of decomposition could lead to major iterations, for example shown in case C4. To evaluate the new perspective of coevolving solutions, a limited number of interactions based on two levels of decomposition would be preferable, reducing complexity.

5. System boundaries: System boundaries make it possible to redefine and cluster challenges, developing them in innovative solutions. System boundaries can either be weak, where they remain conceptual and are modified dependent on the requirements, or strong: based on existing knowledge from the K-space and allow for limited modifications. In the case of weak boundaries, not only the initial definition of the system boundaries is important, also the redefinition of the boundaries where necessary plays an important role during the innovation process.

6. The role of concepts: An approach managing the innovative design has to consider the development of the actual concept. The initial definition of this concept influences performance definition and improves communication between different actors, yet, it is important to define these initial concepts as (flexible) drafts or these predefined solutions end up as the final solution.

Two distinct conclusions are strongly influenced by the social dimension of the interaction, based on how to handle coevolving solutions and interaction in practice.

1. There is no guarantee for success in innovating: Anyone involved in developing innovative solutions should accept there is no guarantee for success when developing new solutions. This is also part of the initial definition of an innovation: the successful implementation of a new idea (Amabile, 1996). Yet, accepting failure as an option is generally not acceptable in commercial projects. Working towards controlled innovation should therefore focus on guiding the process of innovating and not on the final innovation.

2. The role of social interaction and knowledge in innovating: Within all interviews and case studies the short communication lines, interaction, project specific knowledge and person specific knowledge play a role in developing innovative solutions. Often new knowledge is required to develop innovations, yet, the full scope of acquiring this knowledge is often not possible within the confines of a conceptual design. How to handle these challenges, often solved with complex social interactions, points towards an interesting research challenge.

These observations from practice provide a basis for the definition of the main hypothesis in this research, developed in section 5.4.

5.4 Developing the hypothesis

Coevolution and technical & social aspects of the interaction between multiple levels of decomposition appear to play a key role in the development of innovative vessels (5.1). The available literature does not describe these phenomena (5.2). Still, in practice several of these challenges are already solved using a variety of different approaches (5.3). The observations from practice and theory discussed in this chapter imply that to improve the description of innovative ship design, models should incorporate coevolution and content and way interaction occurs between the involved actors, instead of on developments on a single level of decomposition.

The interaction caused by this coevolution appears to have two distinct dimensions: The technical and social dimension of interaction. The technical dimension of the interaction concentrates on the content of the interaction, discussing which information is transferred between the different actors to support coevolution. The social dimension of the interaction concentrates on how the interactions occur, determining how information applied by the actors to support their developments.

The technical dimension shows most promise to develop as an initial step. In this stage, the content of the interaction (in System Engineering defined as 'design feedback' and 'requirements' figure 5-6) is modelled and developed into a design strategy (chapter 6), before being tested in practice (chapter 7 and 8). Further research can then focus on the social dimension of the interaction (chapter 9).

5.4.1 Hypothesis

Based on the observations in the previous sections a working hypothesis could be developed. A working hypothesis facilitates inquiry, stating expectations based on a set of observations. In due time, the new theory developed in further research can be used to construct formal hypothesis and design specific experiments, to validate and justify these findings. The working hypothesis defined for further research concentrates on the technical dimension of the interaction when allowing for coevolving solutions:

To improve the development of coevolving innovative solutions a design process should focus on two levels of decomposition, allow for weak system boundaries and take into account the technical dimension (the content) of the interaction.

To explore this working hypothesis the technical dimension of the interaction is modelled in chapter 6, and tested in chapter 7.

Part III

Towards controlling innovative ship design

Chapter 6

A new design strategy: model and methodology development

"The development of a model and deriving a methodology for evaluation purposes"

Chapter 5 concludes that to improve the development of innovative solutions a design strategy should be based on coevolving solutions on two levels of decomposition. In a first step, an approach is developed based on the technical dimension (the content) of the interaction. This chapter defines a methodology to determine the consequences of intervening in the existing situation (figure 6-1).

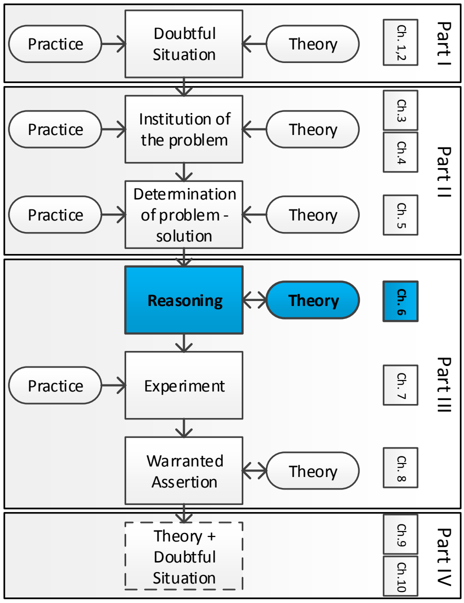


Figure 6-1. Overview of the research stages (equivalent to figure 2-6)

A fledgling model is developed to describe the interaction between two levels of decomposition aimed to solve the objectives defined in section 6.1. The model is reviewed in relation to existing design theory and observations from practice and applied in a methodology to test the original model. This methodology is the basis for two experiments discussed in chapter 7 (figure 6-2).

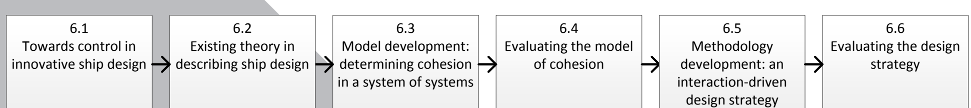


Figure 6-2. An overview of chapter 6

6.1 Towards control in innovative ship design

Ship designers are capable of developing innovative ship designs by supporting coevolving solutions and the social and technical dimension of the interaction, as shown in case C1 – C4. As illustrated below, the industry is by no means comfortable with the situation: innovative ship design is considered a challenging task with many risks, where innovative design just 'happens' (quote 6-1), although a more structured approach would be preferable (quote 6-2). Therefore, the main reason for practice to develop a novel description of ship design and propose a structured methodology is not to develop more innovative solutions, but to improve control during these developments.

> *"Both in the early design phases as well as in the basic-design phases, the development went, as it went. Sometimes, things just "happened". We now try to develop this into 'check' moments, where we consider certain solutions. It was difficult to plan, because we were developing something what we didn't know yet where it was going to end up, and it was without deadlines."*

Quote 6-1. Naval architect, C2, Peters Shipyard (translated from Dutch)

> *"I think that we should change the way we manage such a project, compared to this project, to take control for example on the planning."*

Quote 6-2. Naval architect, C2, Peters Shipyard (translated from Dutch)

The aim of 'control' is to provide a more structured approach to master innovative developments in a project. At this stage, the focus is on determining which parameters are important in understanding innovative design and to increase understanding how this process is conducted in practice. In a later stage, based on this understanding but not part of this dissertation, a managerial control method could be developed based on error detection, performance measurement, corrective action or applying the principles of resilience.

The analysis of the theory and practice discussed in chapter 5 provides insight in which elements would improve control during innovative design projects. Four objectives are identified, which are discussed in more detail in the following subsections and illustrated with examples: the definition of potentially innovative items (6.1.1), structuring the involvement of technology partners and other actors (6.1.2), integration and coevolution within weak boundaries (6.1.3) and the timing of creativity (6.1.4).

6.1.1 Defining what may potentially result in innovative solutions

In the case studies, independent if it was a clever pile upending tool, the LNG propulsion system or a safe anchor handling system, the decision to change different parts of the design was already taken in advance of each project; before solutions were developed. The available, existing solutions (5.1.1) were insufficient for the client and new concepts needed to be developed that result in improved functionality, capability or performance (including costs).

This does not mean that all decisions are taken early: the IJsselhuid, X-bow®, or the new build design of the Pioneering Spirit were implemented in a later stage of the project. This shows a challenging dichotomy: it would be preferable to define specific potential innovations as an objective. However: defining where the innovation has to occur may limit creativity, thus, to be able to improve control during the innovation process, we need to increase knowledge in what exactly happens during such processes, to avoid innovating for the sake of innovation (Hekkenberg, 2012).

6.1.2 Involvement of technology partners and other actors

The vessels discussed in the case studies were developed by a broad range of actors, such as technology partners, classification society, future clients and various other partners.

Different actors often like to be included (for example in quote 6-3) in the early stages of the design process, as they can support and improve the design by implementing their (technical) knowledge.

> *"I would like to be involved in the design; than you can change or modify the design of for example the hull, because that was already finalized when the oil & gas company stepped in."*

Quote 6-3. Team leader, C2, client (translated from Dutch)

Although additional involvement appears to be necessary to develop innovative solutions, the majority of projects (in particular case study C1, C2 and C3, but also the early stages of case study C4) were developed by small and flexible project teams to improve social interaction and communication. The project teams of one technology partner, the client and UDS during the development of the Bourbon Orca as an example. Balancing actor involvement taking into account the required knowledge to develop new solutions and the wish to keep project teams small and flexible is one of the challenges where additional knowledge may improve control.

6.1.3 Support integration and coevolution within weak boundaries

Ship designers involved in developing large, complex vessels performed different tasks during the project, but one of the most often mentioned activities was the evaluation of the impact of new developments in combination with the other elements of the design. Determining this was particularly difficult as it is context dependent: an innovative ship design only has added value if the business case benefits from this, and innovative propulsion system only is applicable in a design that benefits from such a propulsion system. This was visible in all the case studies: In case study C2, the overall design of the Greenstream tanker enabled the use of the LNG propulsion system and in case study C4, the lifting systems were possible because of the overall layout of the vessel.

What makes this complicated, is that the evaluation of innovative solutions often requires new tools and knowledge: an innovation changes the status-quo as it introduces new knowledge based on previously unknown concepts. The available (software) tools and knowledge are often not capable of describing the consequences of the phenomena related to these new concepts, one of such examples from the Delft University of Technology is the development of nonlinear accelerations in head waves, coupled with the development of the Enlarged ship concept (Keuning, 2000) and the Axe bow (Keuning, 2002). In this situation the new knowledge was needed for being able to evaluate these concepts.

6.1.4 The timing of creativity in the design process

To further improve control in the development of innovative designs special attention is required for the creative aspect in design. The main question related to creativity is whether creativity is controllable and manageable. As Florida & Goodnight mention: theoretical views on this subject differ, but both opinions appear to be valid. Many researchers still concentrate on the individual creativity, which is difficult to control. Other start to concentrate on managing creativity in a larger (for example, companywide) setting (Florida & Goodnight, 2005), which could be controlled.

This research assumes that the individual, personal creative act itself cannot be harnessed and controlled, but that the situation where creativity could occur can be organised and structured. This includes not only the steps where creativity may occur, but also incorporates the application and implementation of these creative solutions.

Facilitating the creative steps also means there is a distinct possibility that the 'creative leap' does not occur and that the result of the project is not an innovative solution. A novel description of the ship design process to improve control should concentrate on improving the innovative capability, fostering creativity in a structured environment, instead of aiming for a process that guarantees innovation.

6.2 Existing theory in describing systems

The objective of this chapter is to develop a design strategy which is based on the technical dimension of interaction: the content of the interaction caused by coevolving solutions across the different levels of decomposition. To determine the type of information transferred between coevolving solutions a conceptual model is developed which serves as an annotation system for this information. The first step in developing a conceptual model is to describe an individual system. Several theories in in ship design literature apply an annotation system to identify the different aspects of an object. In this section, four existing approaches are evaluated and applied to describe an individual system.

6.2.1 Describing a system

The elements of a single system are based on four theories, each describing an individual system with their own terminology: System engineering (INCOSE, 2014), Complex systems theory (Rhodes & Ross, 2010), Axiomatic design (Suh, 2005) and the FBS model (Gero, 1990). The terminology used in each theory is described in box 6-1 to box 6-4.

System engineering

The development of a system within system engineering (3.3.2) is based on 4 activities linked to 4 aspects: requirement analysis (linked to requirements), functional analysis and allocation (linked to functions), design synthesis (linked to the design) and system analysis and control (linked to analysis) (DoD, 2001). The aspects are discussed below.

1. Requirements: The requirements are defined by the client to convey what their preferences for the system development. Requirements can prescribe certain solutions or request a certain functionality, the most common however are performance requirements. The performance requirements set values that the eventual design needs to achieve.
2. Functions: The functional decomposition and allocation plays an important role in the SE literature. In ship design, this has been further explored (described in 3.3.4). The functions describe the objectives each individual component needs to perform in a structured decomposition.
3. The actual design: The final step in the design of a sublevel (Figure 3-21) is the design synthesis. Within this step the actual design and the related documentation is generated and described.
4. Analysis: SE considers a 4th element in the form of system analysis and control (balance). This aspect evaluates the actual performance of the design, and compares this with the requirements, providing to balance the design.

Box 6-1. System engineering terminology (section 3.3.2)

Complex systems theory

The complex systems theory (3.4.3) is primarily concentrating on the analysis of a system. The theory recognizes 5 aspects, used to describe a system: structural, behavioural, contextual, temporal and perceptual. The descriptions provided by complex systems theory are discussed below (Rhodes & Ross, 2010).

1. Structural: The structural aspect is closely related to the form of system components and their interrelationships. This aspect identifies the actual design of the object.
2. Behavioural: The behavioural aspect is related to the performance, operations and reactions to stimuli. This aspect provides a description of the actual performance of the design.
3. Contextual: The contextual aspect is related to the surrounding circumstances in which the system exists.
4. Temporal: The temporal aspect is related to the change of properties of the other aspects (structural, behavioural, contextual and perceptual) over time.
5. Perceptual: The perceptual aspect is related to stakeholder preferences and perception. This aspect identifies which aspects are deemed important and should be considered as the objective of the design.

Box 6-2. Complex systems theory terminology (section 3.4.3)

Axiomatic design

Axiomatic design theory was developed by Suh as a more generic perspective on design. The approach identifies design as an interaction between 4 domains: the customer domain, the functional domain, the physical domain and the process domain (Suh, 2005). The 4 domains are discussed below (Suh, 2001).

1. Customer domain: The customer domain contains the desired attributes for the customer.
2. Functional domain: The functional domain contains the functional requirements specified for the product, in general these are the required properties of the object.
3. Physical domain: The physical domain contains the physical variables that satisfy the functional requirements, the 'solution' to the challenges defined in the functional domain.
4. Process domain: The process domain concentrates on how the design, defined in the physical domain is developed using resources and processes.

Box 6-3. Axiomatic design terminology (Suh, 2001; 2005)

FBS Theory

FBS-Theory is a more generic description of the design process which describes design as transformations between a set of expected behaviour, a set of actual behaviour, a set of functions, structure, and a design description. The 5 elements of the FBS model are discussed below (Gero, 1990).

1. Functions: The functions contain the goals or objectives of the design, embodying the expectations of the purpose of the resulting object.
2. Structure: The structure contains the artefacts elements and their relationships. This structure is the direct basis for the design description, but only concentrates on the final design.
3. Expected behaviour: The expected behaviour is formulated or specified based on the functionality.
4. Actual behaviour: The actual behaviour of the object is directly related to the eventual structure. The actual behaviour is the result of analysing the existing object. The expected behaviour and the actual behaviour are not equal, but need to be compared throughout the design process.
5. Design description: The design description is the eventual objective of the design process. This element contains sufficient description of the actual object and the related behaviour so that the artefact can be manufactured.

Box 6-4. FBS theory terminology (Gero, 1990)

Each theory described here has a different aim: system engineering and complex systems theory concentrate on the conjunction of individual systems, but do not describe the subsequent social and technical interaction beyond the system boundaries. Axiomatic design and FBS-theory are founded in the engineering design literature, providing more generic descriptions of design.

The theories discussed here provide some insight in the terminology used in describing individual system design. In each box several recurring elements are discussed. However, none of the theories provides insight in what information is exchanged beyond the individual system boundaries. The terminology used by these theories is by no means consistent. Still the recurring elements are used to identify a new set of terminology for application in this research.

6.2.2 Applying existing theory

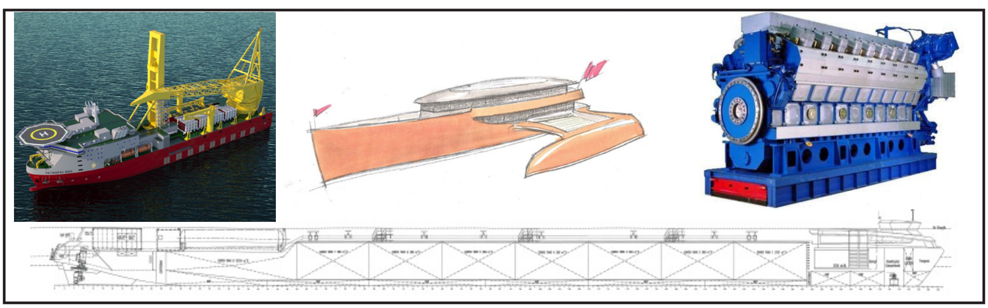
Based on the observations in existing theory the following aspects are determined as key parts describing an individual system. This annotation system based on: (a) Form, (b) Characteristics, (c) Performance and (d) Function is developed specifically for this research and remains consistent in the dissertation:

a. Form: The form identifies the visual shape or configuration of the system (Oxford University Press, 2015).
b. Characteristics: The characteristics identify the features or quality belonging to the system, serving to identify them (Oxford University Press, 2015). In technical systems, these include all identifiable parameters describing the system.
c. Performance: The performance identifies the ability of the system to do something (Oxford University Press, 2015). The performance of a system is a subset of the systems characteristics, based on what the system has to do.
d. Function: The function provides the purpose of the system (Oxford University Press, 2015). The function identifies what the system has to do.

To determine how these aspects relate to the terminology used in the four other theories, each term is discussed in more detail and illustrated with examples.

The "Form" of a system: The form describes the visual shape or configuration of each individual system (Oxford University Press, 2015). The description of form in a system returns in each of the individual theories: System engineering generates the form during design synthesis (box 6-1), both complex systems theory and FBS-theory describe the form as the structural element (box 6-2, box 6-4). Axiomatic design defines the eventual solution in the physical domain (box 6-3).

At this stage, the research focusses on identifying the different elements describing a single system and not in a process or domain; therefore the terminology used in system engineering and axiomatic design was unsuitable. The 'structure' identified in complex system theory and FBS theory is ambiguous, as within the shipbuilding industry structure and structural elements solely describe the steel, aluminium or composite construction. Based on these theories and the definitions found in the Oxford dictionary the choice is made to describe this element as the "form" of the system. The form of a system describes the visual shape or configuration, but it does not identify the level of detail of the description. The form can be a conceptual sketch, 3D rendering or a detailed general arrangement all the way to a finished product (box 6-5).



Box 6-5. Examples of form: Ulstein-design (render), yacht (sketch), an engine and Greenstream (GA)

During the development of a new ship design, observations show that form evolves from a rough sketch into a more detailed design leading to construction drawings and an actual operating vessel.

The "Characteristics" of a system: Each system contains a set of parameters describing the system, in System engineering these parameters are evaluated in the system analysis and balance (box 6-1), Axiomatic design contains this in the physical domain (box 6-3). Both Complex systems theory and FBS theory do not define a full set of parameters, although a subset of these parameters is defined as the (actual) behaviour of the system (box 6-2, box 6-4).

This research concentrates on describing an individual system, not on a process (in the case of system engineering) or a domain (in the case of axiomatic design). The terminology applied in both is therefore unsuitable in describing an individual system. The behaviour defined by both Complex systems theory and FBS theory does provide a limited set of parameters (the parameters influenced by external stimuli) but does not describe all parameters potentially interesting to describe a system (which also include 'internal' parameters). Therefore, a more inclusive term is applied: the 'characteristics', which illustrates all parameters describing the system (Oxford University Press, 2015).

These properties include both the inherent properties of the system as well as the systems capabilities, behaviour and preferred properties: these are all subsets of the systems characteristics. The 'characteristics' are not always defined as definitive parameters: during the development of a new system, characteristics are developed from broad ranges for main dimensions, initial measurements and requirements, towards more detailed descriptions (box 6-6).

Characteristics in ship design (and car design)

1. The SOC5000 has (among others) the following characteristics

Type	Self Propelled Heavy Lift Vessel
Concept Design	Ulstein Sea of Solutions BV
Positioning system	DP2 class (upgradeable DP3 class) or 8-point mooring system
Transit speed	ca. 14 knots
Propulsion thrusters	2 X 5500 kW
Retractable thrusters	3 X 3000 kW
Tunnel thrusters	2 X 2000 kW
Main Generator sets	6 X 4000 kW
Emergency genset	1 X 1000 kW
Lifting equipment	Single mast crane 5000 ton fixed over stern, 4000 ton fully revolving

Length (over all)	180.9 m
Length between p.p.	170.1 m
Beam	46.2 m
Depth (moulded)	16.1 m
Operational draft	6.0 - 9.0 m
Main deck area	ca 5500 m²
Accommodation (normal)	220 persons
Accommodation (max)	400 persons

2. The Wärtsilä 32E has (among others) the following characteristics

Wärtsilä 32, E version, IMO Tier II		
Cylinder bore	320 mm	Fuel specification:
Piston stroke	400 mm	700 cSt/50oC
Cylinder output	580 kW/cyl	7200 sR1/100oC
Speed	750 rpm	ISO 8217, category ISO-F-RM K700
Mean effective pressur	24.9 bar, 28.9 bar	SFO 174 g/kWh at ISO condition
Piston speed	10.0 m/s	

3. The Ferrari Enzo is a two seater, weighs 1365 kg, is standard provided with a Ferrari red paint, sprints from 0-100 km/h in 3.6s and has a topspeed of 350 km/h (among others).

Box 6-6. Three examples of characteristics: SOC5000 design, Wärtsilä 32E engine and the Ferrari Enzo

The "Performance" of a system: The performance of a system is a selection of system characteristics, based on what the system has to do or where it has been developed for. This research identifies what it does (the "something") as the function of the system. Based on what it has to do, how well it does this task can be defined as the performance: both the function and the performance are different aspects of an existing system.

How well a system performs its task is important in all four theories: Complex systems theory and FBS theory identify this as the (actual) behaviour (box 6-2, box 6-4). Axiomatic design discusses the required properties of the system in the functional domain (box 6-3). System Engineering analyses the system and compares a selection of the characteristics with the required performance (box 6-1). The (performance) requirements as defined within System Engineering are not discussed at this stage, but in section 6.3.3.

Both the behaviour and the performance are subsets of the characteristics of the system. Behaviour is strongly related to the reaction on (external) stimuli, while a system performance can also include elements that are not influenced by external stimuli such as colour, styling or weight. Furthermore, behaviour in ship design industry is often linked to the motions of the vessel in a sea state (seakeeping behaviour).

To avoid confusion, this particular subset of the characteristics is defined as the 'performance' of the vessel, a subset based on what the system is supposed to do (the function, as discussed in the subsequent paragraph). For the purposes of this research the performance is a selection of measurable parameters that defines the capabilities of a system in a particular function. This also means that a system with a certain set of characteristics can have different performance when applied for different functions, as shown in Box 6-7.

Performance in ship design (and car design)

1. The performance of the SOC5000 used as a windfarm installation vessel is determined by the operational draft, the main deck area and the dynamic positioning system, while the accommodation, the size of the vessel and the increased lifting capacity is less relevant.

2. The performance of the Wärtsilä 32E applied in a propulsion system is determined by the Specific Fuel Consumption (SFC) in operation and the available power. However, in a high-speed vessel the power to weight ratio is far more important.

3. The performance of the Ferrari Enzo on the track is extremely good, as at these stages the characteristics such as the top speed, sprint speed and cornering capability are important. When using the Enzo to transport goods, performance is limited.

Box 6-7. Three examples of system performance

The "Function" of a system: The function describes the purpose of the system (Oxford University Press, 2015), identifying what the system has to do and what it is developed for. The function of a system plays an important role in the development of a system, it therefore returns in each design approach. System engineering discusses the functional decomposition and allocation (box 6-1), FBS-theory identifies functions as the goals and objectives of the design (box 6-4). Both complex systems theory and axiomatic design define the desired attributes from the client, illustrating what is important for the system design, by the perceptual aspect and the customer domain (box 6-2,) (box 6-3).

The function of the system is identified as the objective or purpose of the system, similar to system engineering and FBS-theory. The function of a system plays an important role during the early stages of the system development. The role of the client in defining the purpose is discussed in more detail in section 6.3.3.

Functions in ship design

1. *Reduced fuel costs and emissions for an inland shipping vessel (Case study C2).*
2. *Installation or decommissioning of platforms in a single lift (Case study C4).*
3. *Improve safety and operations on the aft-deck of an anchor handling vessel (Case study C3).*

Box 6-8. Examples of functions in ship design

These four aspects all play a role in defining an individual system, independent what kind of object is discussed (figure 6-3). The aspects are closely related, but each aspect remains relevant throughout the development of these objects. Section 6.3 develops the relations of these elements within a system of systems in more detail, to serve as an annotation system for the technical dimension of the interaction.

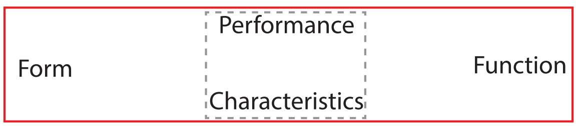


Figure 6-3. Defining an individual system

6.3 Model development: determining cohesion in a system of systems

The four aspects described in the previous section provide the initial basis to determine cohesion in a system of systems. This initial model does not provide a description of the design process, but aims to determine cohesion as a model for the technical interaction of interaction. When developed further, different starting points (discussed in 6.3.3) could lead do different systematic approaches.

In a single level, the four aspects are closely related and influence each other. The performance is a subset of the characteristics based on the function of the system. Characteristics are measured parameters based on the system's form, but a complete set of characteristics can also provide a full description of the vessels form. The elements and their interdependencies provide a description of each system, in each level of decomposition (figure 6-4).

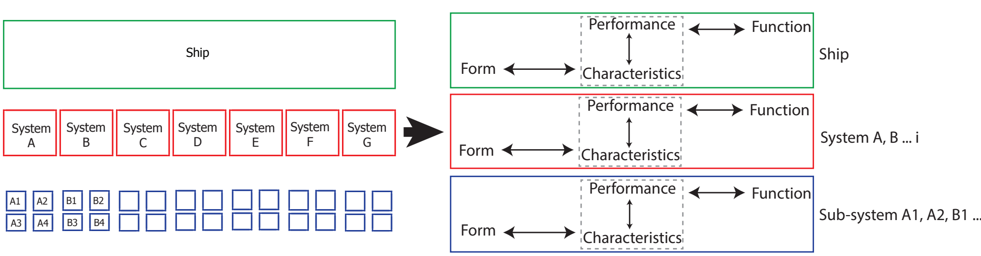


Figure 6-4. Defining systems on each level of decomposition based on Form, Characteristics, Performance and Function

The theoretical frameworks used to develop these elements (system engineering, complex systems theory, axiomatic design and FBS-theory) show that each aspect plays an important role during the design process. However, how the aspects interact beyond their own system boundaries to the different levels of decomposition shown in figure 5-3 and figure 6-4 is not known.

6.3.1 Defining cohesion

The identified elements in each system (6.2) provides a basis to determine the cohesion between an existing system and its respective subsystems (figure 6-5). The cohesion should provide some insight in how system and subsystem interact during the development, beyond their own system boundaries.

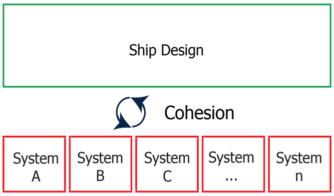


Figure 6-5. Cohesion between ship design and system design

Modelling the cohesion between the ship design and system design is not a representation of the design process, but an approach to model how the elements interact beyond their own system boundaries. How this interaction occurs is based on observations in practice and theory, discussed in chapter 5. These observations lead to the definition of five relations: the decomposition and integration of a system, the contextual relationship and the mutual cohesion between function and performance.

Decomposing and integrating a system: The description of the case studies in chapter 4 is based on a decomposition hierarchy, a theory used in system thinking: an existing design is decomposed into smaller components (Clark, 2009), (figure 6-6). This decomposition applies to the form of the ship and system designs, and is modelled as a direct relation between the ship design form and the system design form, shown in figure 6-7: the ship design form is taken apart into systems, subsystems and components.

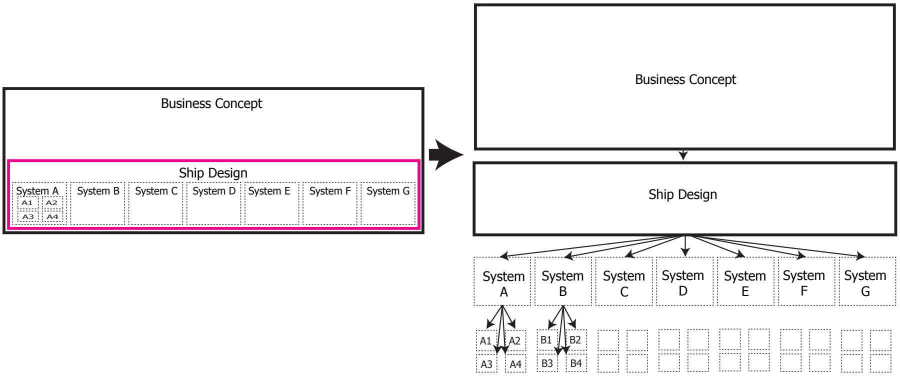


Figure 6-6. The concept of decomposition in a system-of-systems (similar to figure 3-40)

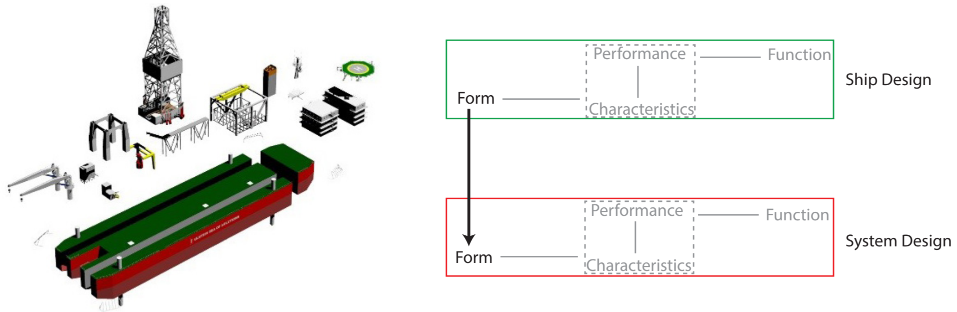


Figure 6-7. Relation 1, the ship design decomposes into systems, subsystems and components

This is also true in a bottom-up integration of existing systems into a new ship design. This relation is applied in the building block approach developed by Pawling (Pawling, 2007). Pawling develops vessels based on predefined systems forms, for example shown in figure 6-8 (left). The relation of a ship design based on system designs is modelled in figure 6-8 (right). In practice, integrating new systems into a ship design is one of the elements in developing innovative solutions, as discussed in point (2) of subsection 5.3.4.

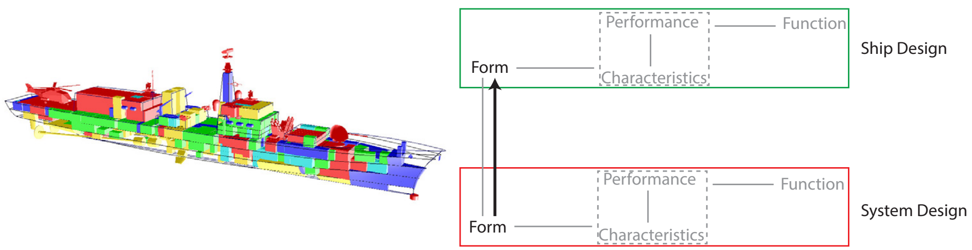


Figure 6-8. Relation 2, the integration of existing systems into a ship design (left: (Pawling, 2007))

Context matters: The case studies show that the context of each development has considerable impact in determining the system's characteristics. This was further strengthened by the different theoretical frameworks evaluated during this research, shown in box 6-9. The importance of the context was also identified in the case studies and the interviews, as discussed in section 5.3.4. In a system of systems the context is provided by the larger system that the object is part of: the higher level-system. To be more specific, the context is provided by the description of the solution (form), one level higher. For example, the X-bow®, LNG propulsion system and the Safe Anchor Handling System (SAHS) are influenced by the overall ship design.

The examples from practice and theory provided in box 6-9 show that all characteristics of the system are influenced by context; independent if the parameters have a limited importance in describing the system or are defined as a (required) performance. The model of this relation is shown in figure 6-9.

Context matters

According to Gillespie: *"A difficulty in developing a more accurate weight estimate is the dependency of the weight of an object on the global location in the ship. A passageway object might weight less if located low in the ship. The reason for this is the additional equipment that might be present when located higher in the ship for reasons of damage control or additional cabling and ducting. Ideally, one should be able to distinguish between systems that do not change weight according to location, and systems that do change weight. This may require a higher level of detail of the ship description." (Gillespie, 2012, p. 195)*

According to Rhodes & Ross: *"The third aspect, contextual, requires the understanding of complexities and uncertainties stemming from the external environment in which the system operates, and the relevant stakeholder needs as driven by this environment. The contextual aspect relates to understanding the system in a fixed context and needs environment." (Rhodes & Ross, 2010, p. 2)*

From case study C3: *The safe anchor handling system was developed independently of the Bourbon Orca, but to determine the characteristics, for example weight, strength and capabilities the system was placed in an existing vessel, and eventually incorporated into the Bourbon Orca, as the integration had considerable impact on the capabilities of the vessel.*

Box 6-9. Context matters, examples from theory and practice

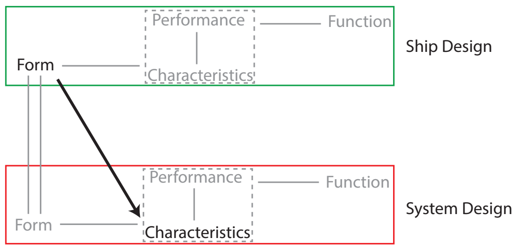
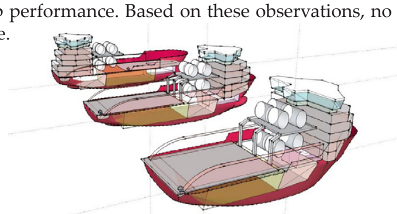


Figure 6-9. Relation 3, the ship design influences the characteristics

The cohesion between performance and function: The model developed in this section explores the cohesion between the system elements on different levels of decomposition. The cohesion between the ship/system performance and ship/system functions are more difficult to define: these relations are not straightforward as both Box 6-10 and Box 6-11 illustrate.

The cohesion between system performances and ship performance

System engineering defines that each system has properties that are attributed to the whole and not to sum of the parts (Checkland, 1999). This is illustrated by the picture below, which shows three designs based on equal system performance, with different ship performance. Based on these observations, no direct relation is defined between the ship and system performance.



Different concepts with equal systems ((Erikstad & Levander, 2012), by (Vestbøstad, 2012))

Box 6-10. Cohesion between system performance and ship performance

The cohesion between system functions and ship function

Functional analysis and functional decomposition has been explored as an independent design strategy, using a formalized top-down approach to functional analysis (Wolff, 2000). Wolff concludes in his research that such an approach to design based on independent functional allocation, is not followed in reality, not even in perfect design conditions. These observations were further strengthened during the interviews with different leaders-of-industry, who discussed that an independent, functional decomposition is impossible. Therefore, no cohesion can be defined between the ship function and the system functions.

Box 6-11. Cohesion between system-functions and ship-function

These observations cause a challenging situation: what influences the performance, how is it defined and what determines the function of a system? How do the ship's performance, the ship's function, the system's function and the system's performance interact? The vessel shown in box 6-10 provides some insight: each vessel is based on the same systems with equal system performance. Each vessel is a platform supply vessel with the same functionality but with different vessel performance such as seakeeping and operational performance (Erikstad & Levander, 2012). Furthermore, the case studies show that the function of the vessel has a considerable influence on the required system performance (box 6-12).

The cohesion between ship function and system performance

In case study C2 the naval architects at Peters-Shipyard aimed to reduce fuel consumption for the inland shipping tanker. To reach this objective, certain system performance was required: The newly developed propulsion system needed to be more efficient and have less emissions than a diesel-direct propulsion system and the newly developed hull should reduce resistance compared to a conventional inland shipping hull.

Box 6-12. The relation between ship function and system performance

There appears to be a close relation between the ship's function and the system performance. The ship's function is provided by the system performances (as the example in box 6-10 illustrates) or the system performances based on the ship's function (box 6-12). The first relation is modelled in figure 6-10, where the vessel function is provided by the system's performance. The second relation is modelled in figure 6-11, which develops the required system performance based on the ship's function, as discussed in box 6-12.

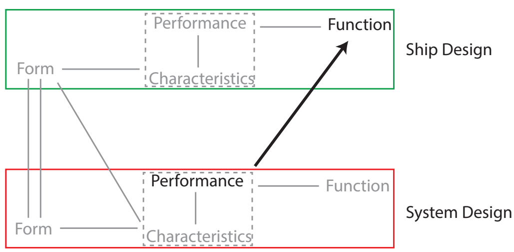


Figure 6-10. Relation 4, the system performance determines in the ship functionality

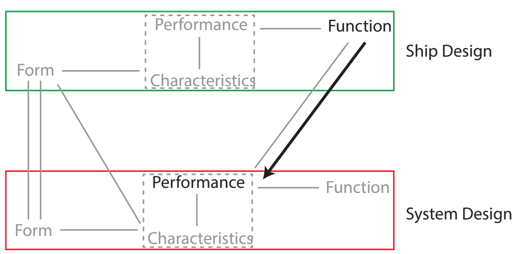


Figure 6-11. Relation 5, a certain function for the ship requires a performance of the systems

The five relationships discussed in the previous paragraphs provide model of the cohesion between two levels of decomposition. The relations are developed concentrating on the technical dimension of the interaction between the ship design and system design. The proposed model of cohesion between the ship design and system design shown in figure

6-12 contains the four terms defining an individual system, complemented with five relations beyond the system boundaries identified in this section. A brief summary of the relations is provided in figure 6-13.

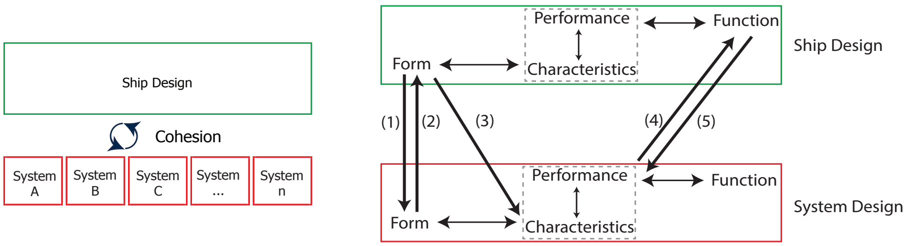


Figure 6-12. The five interactions determining cohesion in a single model

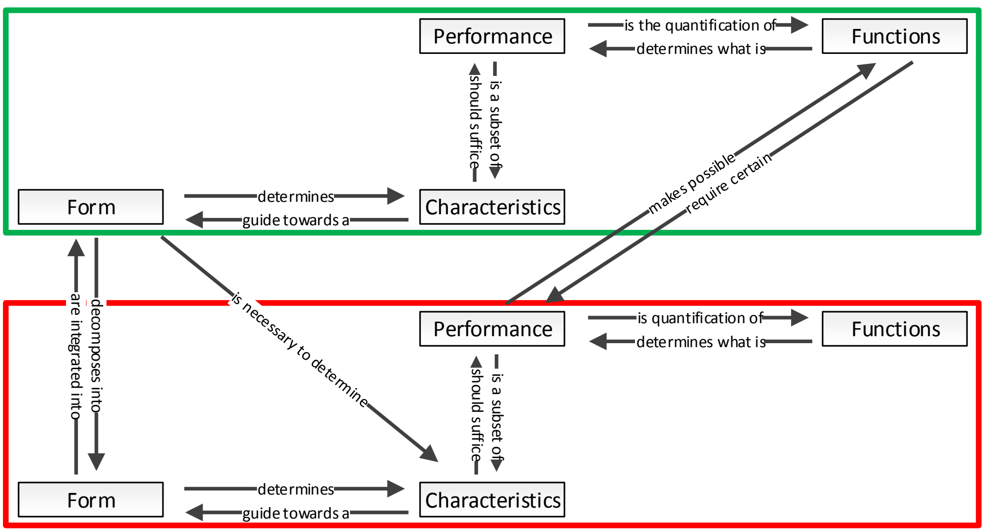


Figure 6-13. Summarizing the relations that determine the cohesion between two levels of decomposition

This model describes the cohesion between the ship design level and the system level. However, the relations defined within the proposed model appear to be independent of the type of system. In a subsequent step, the model is applied to the different levels of decomposition in a system of systems.

6.3.2 Modelling the cohesion in a system of systems (SoS)

Observations in chapter 5 show that in a system of systems developments may arise on multiple levels of decomposition. Developments on different levels of decomposition results in interactions between different levels of decomposition. For development purposes, the system levels are named system X+1, system X, system X-1 and system X-2 (figure 6-14).

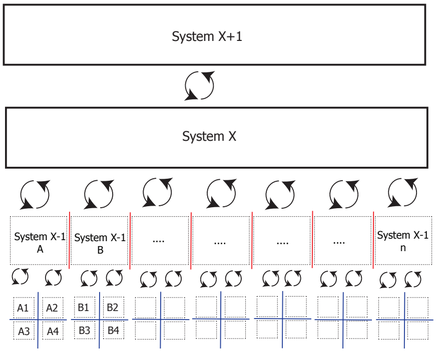


Figure 6-14. Multiple possible sets of coevolving solutions in a system of systems

The relations proposed in section 6.3.1 are independent of involved objects. When applying the relations to the development on multiple levels of decomposition shown in figure 6-14 cohesion in a extensive system-of-systems can be visualized (figure 6-15).

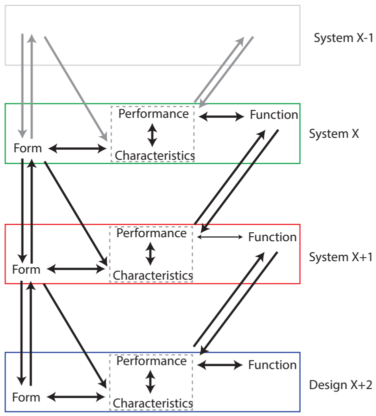


Figure 6-15. Modelling cohesion in a extensive system-of-systems

The model potentially provides insight in the interaction between the levels of decomposition in a broader SoS. However, the model does not provide insight in how to manage two levels of decomposition, or how system boundaries are developed (5.3.4, (4), (5)) (figure 6-16). This is discussed in more detail in section 6.4.2.

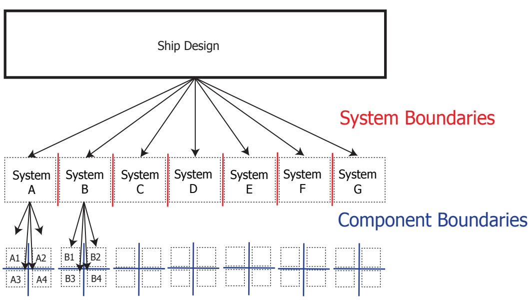


Figure 6-16. Illustrating the initial boundary development

6.3.3 The influence of starting a project: the role of requirements

The model discussed in the previous sections does not describe a design process, but provides insight in the relationships within and beyond system boundaries. To initiate a design process based on this model a starting point has to be defined. Different starting points, often defined as requirements, can occur on all decomposition levels. Requirements in the ship design take many shapes, in the system engineering literature these different types requirements are identified which include functional, performance, usability, interface, operational, adaptability requirements (BKCASE Editorial Board, 2014). This research assumes that clients can request a product, characteristics or define performance and function on each level of decomposition, as shown in figure 6-17.

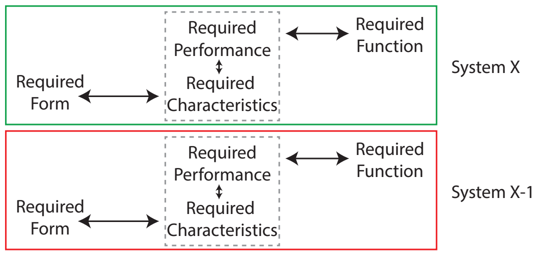


Figure 6-17. Client's requirements in describing a system

These different starting points are also observed in practice:

1. In case study C1, the project was initiated based on the SOC5000 concept, (ship design form). Examples from other form requirements, seen in commercial projects include the 2500 ton tower crane, located at centreline or the Ulstein X-Bow®.
2. In case study C1, length, width and depth were defined in the basis of design, which were characteristics of the ship that did not have a direct impact on the required function.
3. Performance requirements are the most common in the ship design industry, one example is the DP capability such as: DP Class 2 dynamic positioning system, which is defined as allowing for any single active component failure, or a certain operability of the vessel.
4. In case study C2, the objective of the ship design was to reduce the environmental footprint and fuel costs of an inland shipping tanker; a ship level function. In case study C3, the objective of the SAHS system was to reduce high-risk operations on the aft deck of an anchor handling vessel; a system level function.

Different starting points observed in practice result in different design processes. If a client requests a solution, such as the SOC5000 concept, a 2500 ton crane or the ULSTEIN X-Bow® there is a limited amount of design freedom, as the developments are based on existing solutions, although the uncertainty in the design is low. If a client requests certain characteristics, the challenge is less constrained but large variations on the existing designs are not possible, although there is still some potential for conceptual developments. Performance requirements provide more freedom, as they provide a subset of the characteristics that complement the client's business case, which provides more room for conceptual solutions. Functional requirements provide the most design freedom, as this only defines the purpose of the system, without constraining the eventual solution: this provides the most opportunity for conceptual developments, although the uncertainty in the design is high. The different types of requirements shown in figure 6-17 are compared to the design freedom in figure 6-18.

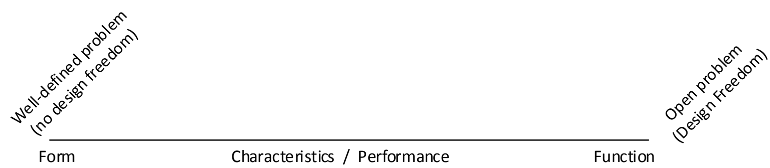


Figure 6-18. Different requirements and their relation to design freedom

The type of requirement plays an important role in the development of innovative solutions, as discussed in 5.3.4, point (6). A well-defined problem with limited design freedom does not allow for undecidable concepts to be developed but reduces uncertainty in the expected results. More design freedom, for example by requesting system functionality, provides opportunities to develop new solutions but also increases uncertainty in what solutions are expected. As mentioned, different starting points in the model result in different design processes. These different starting points are also visible in the design processes described in chapter 3 and the case studies described in chapter 4, resulting in specific design processes for specific applications and practices. These developments are discussed in more detail in section 6.4.

6.4 Evaluating the model of cohesion

Section 6.3 develops a model to describe the relations of a system beyond its own boundaries. This model is used to evaluate a new perspective on the ship design process which allows for coevolution of solutions on different levels of decomposition. In this section, the model is compared to existing ship design strategies to evaluate the relations defined in the model. Furthermore, this chapter discusses selection of interacting levels of decomposition and the selection of system boundaries, based on observations in practice.

6.4.1 Evaluating cohesion: a comparison with ship design strategies

The model defined in the previous section correlates with the observations related to the technical dimension of the interaction: the evaluation of the design, integration of new systems and the role of the context. The theoretical review related to coevolution and technical interaction shows that ship design theory does not provide a direct answer to describe these phenomena, because the development of multiple levels of decomposition does not occur in parallel but sequentially. To evaluate the relations in the model of cohesion, it is compared to three design theories applied in ship design: the design spiral (3.2.1), classical system engineering (3.3.3) and packing (3.4.2).

The design spiral: The Evans design spiral models the iterative behaviour of the ship design of a typical, surface cargo ship problem (Evans, 1959). This review concentrates on the first synthesising cycle: the first steps through the design spiral. To compare the design spiral and the model of cohesion (shown in figure 6-19) the terminology is reviewed in table 6-1. The ship design spiral does not distinguish between characteristics and performance, nor does it mention functionalities of either the ship or the systems.

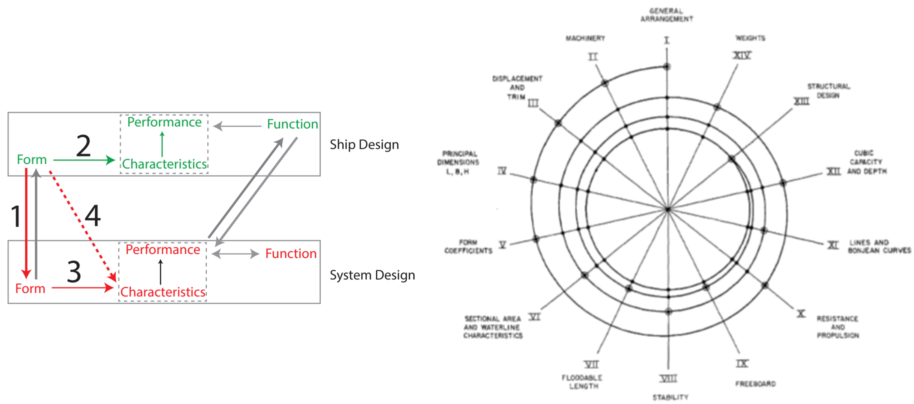


Figure 6-19. The model of cohesion and the design spiral (Evans, 1959)

The elements of the ship design spiral of Evans are identified in the left part of table 6-1. The individual elements are related to the four aspects of a system, both in ship design and system design levels. The steps between the elements in the design spiral (the interactions) are provided in the left part of table 6-2. These steps are correlated with the relations defined in the model of cohesion.

Table 6-1. Comparing elements of the design spiral and to the model of cohesion

Design Spiral			Model of Cohesion	
Element		Activity	Level of decomposition	Element
I	General Arrangement	General Arrangement is a description of the ship-design	Ship-Design	Form
II	Machinery	Machinery describes the principle solution of the propulsion system	System Design, system 1	Form
III	Displacement & Trim	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
IV	Principle Dimension (L, B, H)	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
V	Form Coefficients	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
VI	Sectional area and waterline characteristics	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
VII	Floodable Length	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
VIII	Stability	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
IX	Freeboard	Analysis of the overall ship-design	Ship-Design	Characteristics/performance
X	Resistance & Propulsion	Analysis of the propulsion system, defined in II	System Design, system 1	Characteristics/performance
XI	Lines and Bonjean curves	Development of the Hull-form, a new system	System Design, system 2	Form
XII	Cubic capacity and depth	Analysis of the hull-form	System Design, system 2	Characteristics/performance
XIII	Structural Design	Development of the structure, a new system	System Design, system 3	Form
XIV	Weights	Analysis of the structure	System Design, system 3	Characteristics/performance

Table 6-2. Comparing steps of the design spiral to the relations in the model of cohesion

Design Spiral		Model of cohesion		
Step	Activity	Relation: (from - to)		Relation defined in the model
I -> II	Based on the general arrangement (GA) the machinery is selected	Ship (Form)	System No. 1 (Form)	Yes (No. 1)
II -> III	The displacement and trim is analysed based on the GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
III -> IV	The principle dimensions are determined based on the GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
IV -> V	Sectional area and waterline characteristics are estimated based on GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
V -> VI	Form coefficients are determined based on the GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
VI -> VII	Floodable length is determined based on the GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
VII ->VIII	Stability is determined based on GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
VIII -> IX	Freeboard is determined based on GA	Ship (Form)	Ship (Characteristics & Performance)	Yes (No. 2)
IX -> X	Resistance & Propulsion is analysed based on the machinery in step 2	System No. 1 (Form)	System No. 1 (Characteristics & Performance)	Yes (No. 3)
	and the GA	Ship (Form)	System No. 1 (Characteristics & Performance)	Yes (No. 4)
X -> XI	Hull-design is made, based on the GA	Ship (Form)	System No. 2 (Form)	Yes (No. 1)
XI -> XII	Hull-design is analysed based on context of GA	System No. 2 (Form)	System No. 2 (Characteristics & Performance)	Yes (No. 3)
		Ship (Form)	System No. 1 (Characteristics & Performance)	Yes (No. 4)
XII -> XIII	Structural design is made, based on the GA	Ship (Form)	System No. 3 (Form)	Yes (No. 1)
XIII -> XIV	Structural design is analysed, in the context of the GA	System No. 3 (Form)	System No. 3 (Characteristics & Performance)	Yes (No. 4)
		Ship (Form)	System No. 3 (Characteristics & Performance)	Yes (No. 1)

The comparison shows that the steps in the design spiral are represented in the model of the cohesion. The design spiral concentrates on the left part of the model of cohesion: the relation between characteristics and form on two levels of decomposition. The design spiral is initiated with the ship form and (propulsion) system form. The solutions are evaluated top-down, with the advantage that the context is available to improve the applicability of the analysis. Still, such an approach is less suited for innovative, conceptual elements as it only allows limited design freedom, but more suited for balancing and optimizing an existing design.

Classical system engineering: Classical system engineering is a top-down approach focussed on the project management during the life-cycle of the vessel. The design is illustrated by the left part of the V-diagram shown in the left part of figure 6-20 (Griethuysen, 2000), with independent developments on each level of decomposition, shown in the right part of figure 6-20. The levels of decomposition are compared to the levels in the model of cohesion in table 6-3.

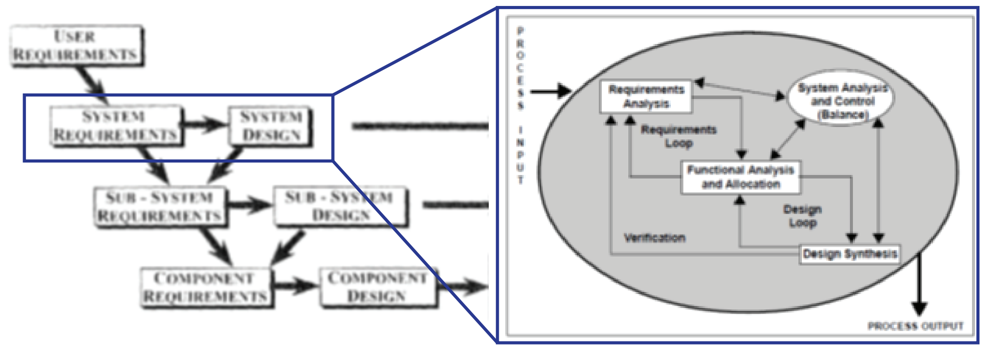


Figure 6-20. The development phase of the V-diagram (Griethuysen, 2000) and the design of a level (DoD, 2001) (equivalent to figure 3-20 and 3-21)

Table 6-3. The levels of decomposition in system engineering in comparison with the model of cohesion

System Engineering	Model of Cohesion
Level of decomposition	**Level of decomposition**
User Requirements	Business case
System Requirements / System Design	Ship-Design
Sub-system Requirements / Sub-system Design	System-Design
Component requirements / Component Design	Component-Design

The top-down approach envisioned in system engineering develops and designs each individual level separately and sequentially (Mar, 1997), (Griethuysen, 2000), (DoD, 2001). When applying a top-down approach, all elements of the higher level are known, making it possible to derive a preliminary form, provide context and determine the performance requirements at a lower level, the three relations shown in figure 6-21.

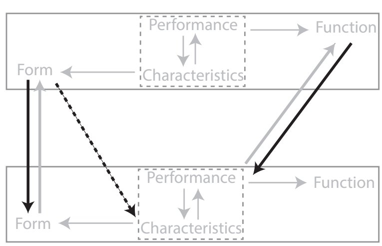


Figure 6-21. The relevant relations in the model of cohesion in a top-down approach

The development of an individual system described in the right side of figure 6-20 is based on a set of performance requirements, defining system functions, synthesising a design and evaluating this design. In general, the requirements are expected to define the performance required for each system. Based on the required performance, function, characteristics and form are developed. In classical system engineering there is no interaction between different levels of decomposition, only a transfer of knowledge. There is only input from the previous design which provides context, constraints and required performance to develop the system further, and output in the form of design feedback. The top-down approach limits the innovation space, as it is not only influenced by the overall functionality and the context, but also by the form: any solution has to fit within the overall, predefined vessel.

Packing: The packing approach is based on the V-diagram shown in figure 6-22. Packing concentrates on generating integrated and valid layouts in conceptual ship design.

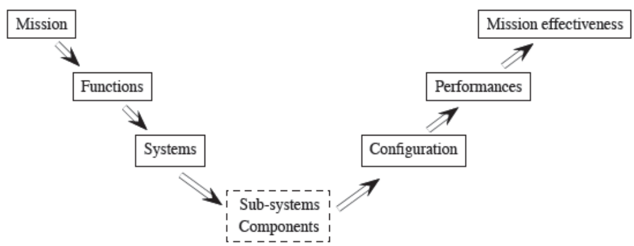


Figure 6-22. The V-diagram used in packing (van Oers, 2011) (similar to figure 3-35)

The diagram appears to be similar to system engineering, but the V-diagram contains different values in each block. The mission, system, subsystems and components are integrated wholes, which includes all four aspects defined in this research, similar to classical system engineering. The functions, configuration, performances and mission effectiveness concentrate on specific aspects of the ship design and the business-case (table 6-4). According to Van Oers, the terminology used to describe "functions" is more akin to performance, as these are: "*Functions that must be fulfilled to complete the mission successfully*" (van Oers, 2011, p. 3).

Table 6-4. The elements in the V-diagram of packing compared with the model of cohesion

Packing - V-diagram		Model of Cohesion	
Element	**Activity**	**Level of decomposition**	**Element**
Mission	Determine what should be achieved	Business-case	Integrated whole
Functions	How it will be achieved	Ship-Design	Performance
Systems	Chose systems that are integrated in the ship	Systems	Integrated whole
Sub-systems / components	Chosen in cooperation with systems to be integrated	Sub-systems/components	Integrated whole
Configuration	Creating the actual ship by integrating (sub) systems and components	Ship-Design	Form
Performances	Predict to the extend which functions are fulfilled	Ship-Design	Characteristics / performance balance
Mission Effectiveness	overal ability to perform the mission; the mission effectiveness	Mission	Performance

The design process in packing allows for an innovative ship design layout, evaluating characteristics and performance of the design; still, it is based on a known business case (or mission) with known systems, subsystems and components. The approach does not discuss or describe interaction between different systems.

6.4.2 The selection of coevolving solutions and generating system boundaries

The review of the model of cohesion with respect to the design spiral, classical system engineering and packing shows that the model covers the relations in these theories. The model appears to cover the more relations between coevolving solutions, providing additional guideline beyond other theories. Still, section 6.3.2 discusses that there are several actions in handling coevolving solutions observed in practice, but not taken into account in the model: the selection of the coevolving solutions and how system boundaries are defined.

Selecting coevolving solutions: the model of cohesion appears to be sufficiently generic to describe cohesion of any system of systems. Still, the observations from the case studies show that to improve the coevolution, the design process should focus on conceptual developments on two levels of decomposition. Selecting systems that are going to coevolve (figure 6-23) would concentrate creative activity while at the same time defining the acceptable innovative solutions. This also means that no conceptual development is considered in other levels of decomposition: solutions on these levels are selected from existing, known solutions.

The reasoning for selecting coevolving levels of decomposition is not modelled at this stage of the research. For the purposes of this research, the selection is accepted as a starting point for developing the design strategy. Based on my observations, the selection of where innovation will occur is based on discussions with the client, however, to determine how this occurs would require further research.

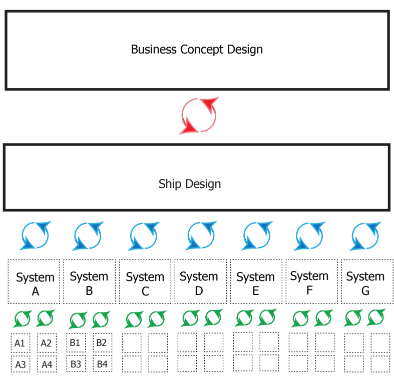


Figure 6-23. The selection of coevolving solutions

The role of system boundaries: The system boundary defines which entities are part of the systems and which are part of the surrounding environment (Gaspar, 2013). How system boundaries are developed is not modelled at this stage of the research, and should require further research.

Documentation related to system boundaries in ship design practice is limited, therefore the development of an initial theory to describe system boundary definition is complex and beyond the objectives of this dissertation. However, based on the model of cohesion, it is expected that the system boundaries are defined in the step from ship form to system forms (figure 6-24, (A)) or the step from ship function to system performance (figure 6-24, (B)). The context primarily influences the definition of the characteristics, and is expected to have limited influence on the system boundaries.

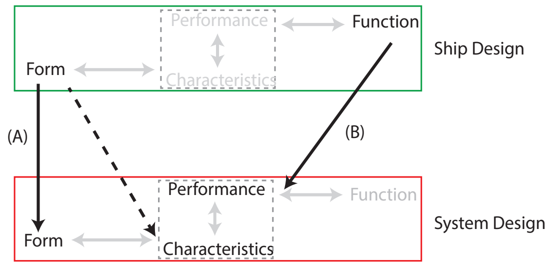


Figure 6-24. The relations with an expected influence on system boundaries

An initial exploration of how system boundaries may be evaluated uses network theory (Killaars, 2014), which provided some insight in the properties of systems and their respective boundaries. Still, additional research is required, for example on the role of system boundaries for different observers (Checkland, 1999).

6.5 Methodology development: an interaction-driven design strategy

The previous sections develops a model by identifying the interaction of system elements beyond the system boundaries. The model of cohesion is based on observations from practice and reviewing the available theory. The model includes the six observations related to the technical dimension of interaction discussed at the end of chapter 5. Still, the model of cohesion does not provide a process to develop a new system. To develop a design strategy based on the model of cohesion, the approach concentrates on two coevolving solutions with a single interaction, in this case: system X and system X-1 (6.4.2). To allow for innovative design, the process is initiated based on the system X's function (6.3.3). Based on these premises, a design strategy is developed following the interactions from the model of cohesion. The process is based on 6 steps (1-6). Each step is discussed below in more detail.

1. **Selecting coevolving solutions:** The first step in developing the design strategy is the selection of the two coevolving levels of decomposition. The design strategy is based on coevolving system X and system X-1. It is important to conduct this step in cooperation with the client, to make sure that the new concepts developed for the project are accepted. In projects, developments could for example focus on new ship design based on new systems, introduce new mission equipment with new components or develop a new business case while exploring new ship types (figure 6-25).

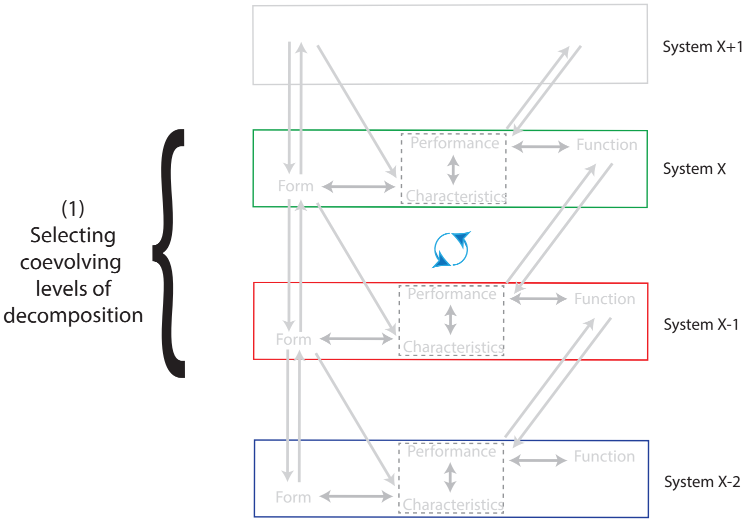


Figure 6-25. Step 1, selecting coevolving solutions: system X and system X-1

2. **Defining the system X's function:** The starting point for the design strategy, after selecting which solutions are coevolving, is the system X's function or objective that needs to be achieved with the final solution. System X's function describes the direction the eventual design is judged on. For a ship design, this could be operational costs, building costs, exploration drilling, production drilling, supply to large offshore platforms, crew tendering or any other objective for the vessel, system or component (figure 6-26).

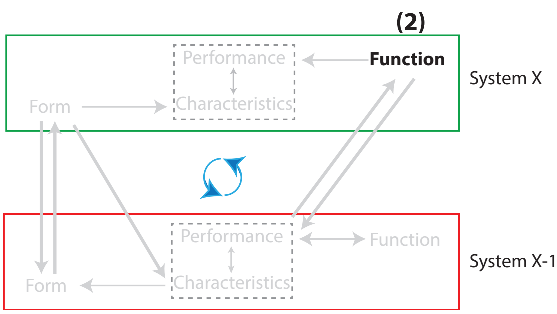


Figure 6-26. Step 2, defining the System X's function

3. **System boundaries and performance parameters:** Based on the vessel's objective a broad spectrum of performance parameters can be identified: performance parameters that support this objective. These performance parameters are developed into sets, as a starting point to develop system X-1 solutions (figure 6-27). At this stage the system boundaries are identified, as discussed in subsection 6.4.1. The development of system boundaries is currently based on the experienced ship designers, but as mentioned before, further research is required to explore how to develop specific system boundaries. At this stage of the project, the system boundaries are conceptual (undecided) and are expected to change in the project; the boundaries are weak.

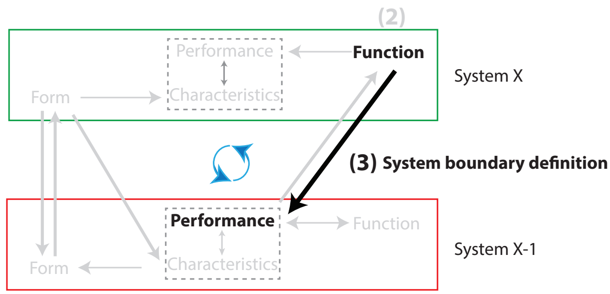


Figure 6-27. Step 3, defining system boundaries and clustering performance parameters

4. **System developments:** The individual set of performance parameters are a starting point for the creative development of the different system X-1's. These developments have to be context independent and should cover a broader range of applications, as at this stage the full context for the system developments is not available yet. Such an approach provides the system designers with more freedom (as discussed in 6.3.3), while maintaining control over the individual system designs (figure 6-28).

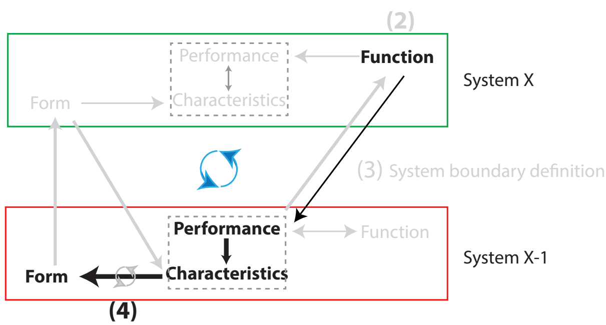


Figure 6-28. Step 4, developing solutions for system X-1, without contextual information

5. **Integration:** The system developments are integrated into the vessel design (5.3.4, point 2). At this stage, the system X-1's performance is revaluated using the specific context provided by the integrated solutions. During the integration designers have more freedom to select and integrate novel system solutions and to develop novel layouts. Based on the integration, feedback is provided to the system X-1's developers about the newly developed context, to improve fit and increase viability of the conceptual system X-1's developments (figure 6-29).

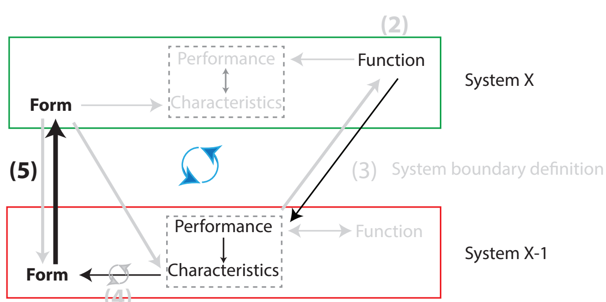


Figure 6-29. Step 5, Integrating system solutions into the overall ship design

6. **System X's performance:** Based on the integration of multiple system X-1, the performance of system X is calculated. To enable this, additional tools may be required to evaluate the objectives defined in step 1. These calculations are key for the interaction with the client, as they provide insight in how system X performs in the objectives set by the client (figure 6-30).

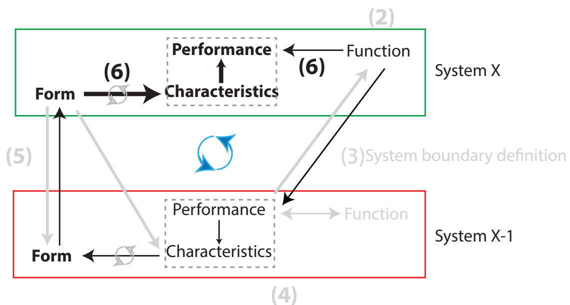


Figure 6-30. Step 6, defining performance of system X

The design strategy discussed in figure 6-26 to figure 6-30 is summarized into a single representation in figure 6-31. The strategy incorporates the technical dimension of the interaction with the aim to improve control during the development of innovative solutions on multiple levels of decomposition.

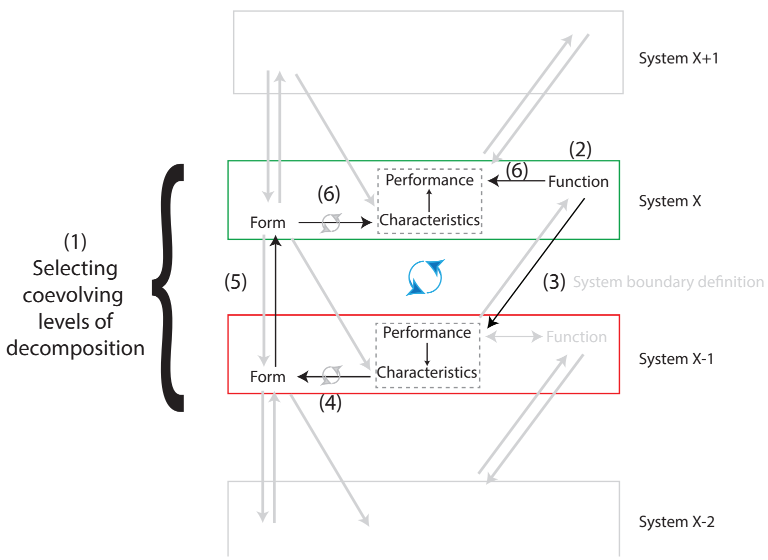


Figure 6-31. The design strategy based on the model of cohesion

The six steps of the design strategy, visualized in figure 6-31, are developed into a linear approach for application within practice. In a first step, the model is rotated 90 degrees, shown in figure 6-32. The design strategy is applied to a specific application: projects concentrating on coevolving ship design and system design, and structured based on time (step 2-6) in figure 6-33. The design strategy shown in figure 6-33 is the basis for evaluation in practice.

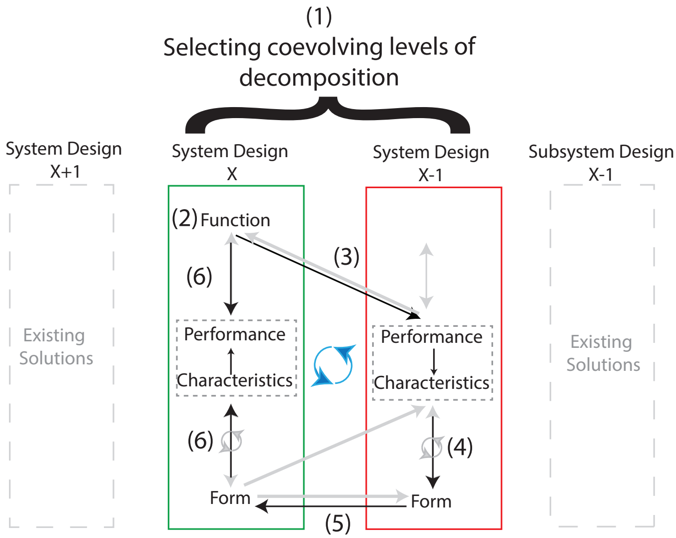


Figure 6-32. Towards a more linear design strategy; rotating the design strategy

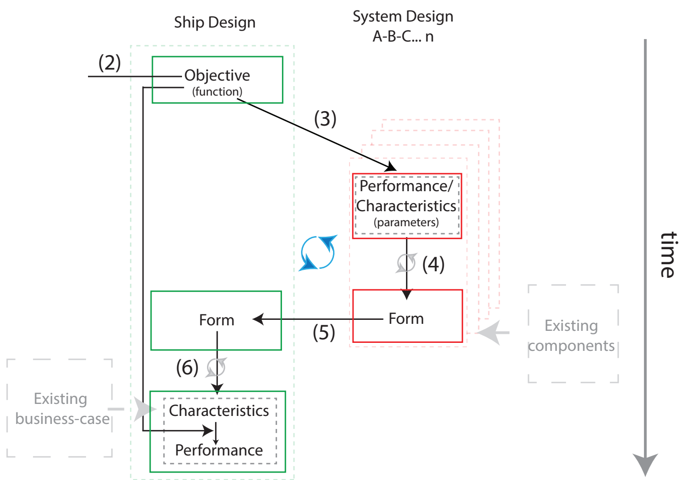


Figure 6-33. Representation of the six steps of the design strategy in time

6.6 Evaluating the design strategy

This chapter models cohesion in a system of system, to determine the technical dimension of the interaction between two levels of decomposition. The model is applied in a design strategy to test during the development of innovative vessels. To evaluate this strategy it is positioned with respect to other ship design theories, before a reflection is made with respect to the original four objectives from section 6.1. However, as the interest of this research is in practice an intervention in the current practice is planned and developed, testing the design strategy.

6.6.1 The design strategy compared to other ship design strategies

The design strategy developed in this chapter is based on two coevolving levels of decomposition, in this case applied to guide ship and system design. The approach is visualized with respect to CK theory in figure 6-34.

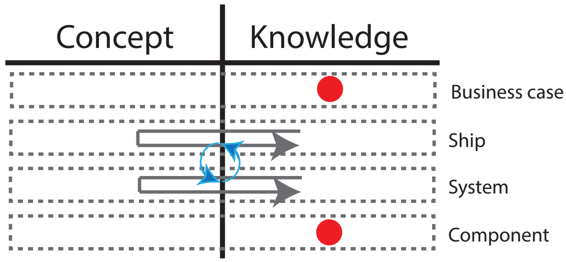


Figure 6-34. Comparing the design strategy to other ship design approaches, CK theory analysis

The design strategy is most akin to requirement elucidation (3.3.5), which develops the requirements (based on the business case) and the ship design in parallel. Still, the strategy developed in this dissertation can be applied in different levels of decomposition and is initiated based on interaction, not specifically the development of the ship, unlike requirement elucidation. As such, it can be seen as an extension of creative ship design (3.2.2) and system based design (3.3.1), extending design beyond the boundaries of the ship design. The design spiral (3.2.1), decision based design (3.2.3), system engineering (3.3.2) and complex systems theory (3.4.3) concentrate on conjunction: the step from the concept space into knowledge space. The proposed design strategy would be positioned before these approaches: in decision-based design this phase is described as the meta-design.

In due time, the model and the proposed methodology could be developed further into a complete method, controlling design beyond system boundaries. At this stage, the methodology requires additional testing an evaluation, at first to determine its value in practice.

6.6.2 Reflecting on the four objectives

In a first evaluation, the design strategy is evaluated with respect to the four objectives defined in section 6.1:

1. **Defining what may potentially result in innovative solutions:** The strategy shown in figure 6-33 concentrates on the interaction between ship design and system design. The approach allows for conceptual designs on both levels: the ship design controlled by functionality, the system design driven by sets of performance parameters; allowing for coevolution of both. As such, the approach shows promise in determining where innovative solutions can be developed, without constraining the eventual objects.
2. **Structured involvement of technology partners and other actors:** The involvement of technology partners (beyond the client and the ship designers) is expected during the development of individual systems and the analysis of the overall ship design, especially if both have an innovative character. During the development of system boundaries in step 3 knowledge gaps in the system developments can be identified. Furthermore, in step 6 tools are necessary to evaluate the ships performance, based

on new functionality. During both steps, the identification of knowledge gaps shows promise in providing for a structured involvement of technology partners.

3. **Support integration and coevolution within weak boundaries:** The approach in figure 6-33 is based on the coevolution of both ship design and system designs. The initial system boundaries are defined based on sets of performance requirements. The lack of a general arrangement until the integration phase in step 5 allows for period of conceptual integration, before the final solution is developed. The lack of the general arrangement also allows the involved actors to define more flexible system boundaries; when necessary, system boundaries can be modified to accommodate innovative systems, unlike a decomposition based on an existing design, where system boundaries are strong and are difficult to change. The design strategy therefore appears to improve the integration and coevolution of solutions within weak boundaries.
4. **The timing of creativity in design:** The approach concentrates on allowing creative, innovative solutions to develop on both a system level and a ship design level. Based on the model, these solutions are developed in step 4 and 5, where new system solutions are developed with limited constraints and during an integration phase where a new layout is developed for the ship based on the innovative system solutions. After this process, based on the integrated solution, optimization and balancing may occur within the new framework. However, these activities are not fully conceptual, as the solutions are already known. The approach allows for creativity and creative solutions during distinct steps in the design strategy. It appears that the approach improves timing of creativity during this process.

6.6.3 An intervention into practice: testing the design strategy

When compared with existing ship design processes the design strategy shows that it is based on a new perspective on ship design, furthermore it shows promise in achieving the four objectives defined in section 6.1. However, the value of the theory can only be defined if the design strategy is tested in practice, to determine value and applicability. According to the Deweyan inquiry, the experiments aim to intervene in current practice to determine if the developed theory is sufficiently relevant and usable; if the theory is sufficiently relevant and flexible for use. The design strategy, applied to the coevolving ship design and system design, developed in this chapter is applied in two commercial projects, discussed in chapter 7 and reviewed in chapter 8.

Chapter 7

Controlling innovative ship design in practice

"An intervention into practice: experimenting with the new methodology"

Chapter 6 develops a design strategy based on coevolving solutions in ship design and system design to improve innovative ship design. The approach is tested in two projects: both interventions in the development of a drillship for harsh weather conditions (Ulstein AXDS) and the development of a vessel for the installation of rocks (SRI-vessel). The interventions are a test if an approach based on coevolution and interaction, as described in chapter 5 and developed into a developed into an interaction driven design strategy in chapter 6, has value for practice (figure 7-1). The analysis is provided in chapter 8.

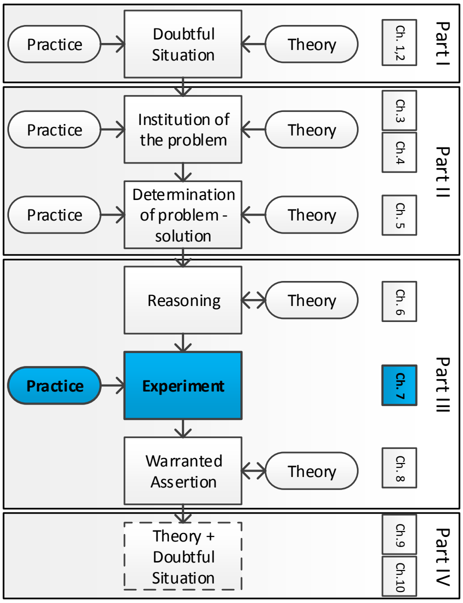


Figure 7-1. Overview of the research stages (equivalent to figure 2-6)

The chapter discusses the development of the experiments (7.1), before discussing the individual cases (7.2 - 7.3) and drawing the first cross-case conclusions (7.4) (figure 7-2).

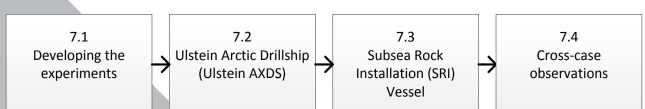


Figure 7-2. An overview of chapter 7

7.1 Developing the experiments

Developing experiments in practice is a challenging situation (7.1.1). To resolve these challenges the two experiments are developed using a case study protocol illustrated in subsection 7.1.2. The experiments are based on the interaction-driven design strategy developed in chapter 6 (7.1.3). The selection of the experiments is discussed in 7.1.4.

7.1.1 Challenges of testing in practice

As part of the Deweyan research approach developed in chapter 2 the design strategy developed in chapter 6 is tested in practice (figure 7-1) to verify the value for practice it aims to describe. Testing such an approach in practice evaluates fit, relevance, flexibility and workability of the theory, but it also has some inherent challenges. These challenges, already identified in section 2.2.2 are in particular important when testing new theory in practice. Both challenges are related to the position of the researcher/practitioner, who needs to mitigate biases and take his impact on the research matter into account.

The projects are part of the Ulstein Sea of Solutions inherent business and are not oriented towards acquiring scientific knowledge. Each individual project is in addition to the scientific objectives from this research influenced by commercial, company and personal objectives. To evaluate the influence of the researcher, but also to provide some insight on factors in the projects two experiments are conducted: The first intervention is done with active guidance and involvement from myself, the second experiment is a project based on the same theory, but without active guidance.

The decision to apply the methodology developed within this research is not the researchers' to make, but is made by the general manager of Ulstein Sea of Solutions. The projects are conducted within practice with the available and suitable employees for the work. As a researcher, this means that there is no control over the project teams involved in the development, in addition the project teams composition is expected to change over time and in each project.

7.1.2 Evaluating the intervention

The two experiments in this chapter are developed according to the case study protocol discussed in 2.3.3 and already applied in the four cases in chapter 4 and the reference case in chapter 5. The protocol is defined by Yin (Yin, 1994) shown in figure 7-3. The sections corresponding to the 5 steps of the procedure for each project are provided in table 7-1.

Figure 7-3. Case study procedure (Yin, 1994) (similar to figure 2-5)

Table 7-1. Steps in the case procedure and the related sections for each case

Step		Intervention 1:	Intervention 2:
1	Framework	Chapter 6, summarized in section 7.1.3	
2	Case selection	Section 7.1.4	
3	Data collection	Section 7.2	Section 7.3
4	Case reporting	Section 7.2.1, 7.2.2	Section 7.3.1, 7.3.2
5	Cross-case conclusions:	Section 7.5, Chapter 8	

The projects are elaborated in separate reports: these reports are commercial in confidence, for access or more information please contact the author. To provide a complete overview of each case in this chapter is not preferable, therefore a summary of the data and the case report is provided in each section. The cross-case conclusions are based on these reports, developed from datasets including interviews, design data and project management data.

To illustrate the observations of involved actors a series of interviews were conducted after the project finished. Several quotes from the interviews are selected and, if necessary, translated to illustrate the experiences of the involved actors. The descriptions and analysis of these experiments concentrated on the content and not on the social elements during the interviews, therefore the quotes are restructured to improve readability. To reduce the influence of the researcher, all quotes were reviewed and approved by the interviewees (figure 7-4). The appendix contains both the original and the restructured (and reviewed by the interviewees) quotes discussed in this dissertation. The approach applied to apply the interviews is similar to the approach applied in chapter 4.

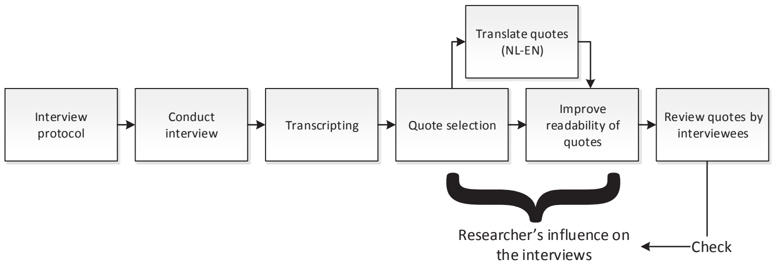


Figure 7-4. Applying quotes derived from interviews (similar to figure 4-11)

7.1.3 Framework

The design strategy developed in chapter 6 aims to improve control during the conceptual development of innovative ships, while still maintaining the inherent capability of the industry to develop innovative designs. To improve control during these projects, the intervention aim to achieve the following four objectives, discussed in more detail in section 6.1, and summarized in the list below:

1. Defining what may potentially result in innovative solutions
2. Structured involvement of technology partners and other actors
3. Support integration and coevolution within weak boundaries
4. The timing of creativity in design

The implemented methodology is a design strategy based on the coevolving ship design and system design, developed in chapter 6. This conceptual design strategy (for the purposes of the experiments defined as the "Ulstein Design Process" or "UDP", figure 7-5) is implemented to improve the control in the early design stages, while maintaining sufficient room for creative and conceptual solutions.

From a research point of view, the interventions have the aim to verify if the developed model and methodology has value for practice. The industry is already capable of developing innovative designs, but applying a designated process to which structures these developments should improve control, while still maintaining the innovative capacity could be very valuable. The projects were analysed to review the effect of the design strategy on the product development.

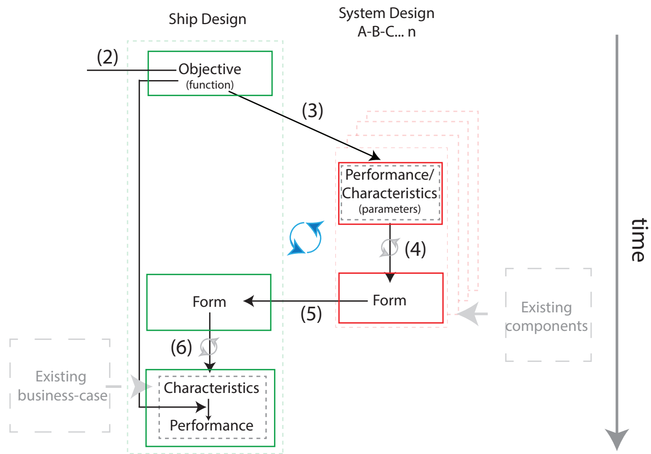


Figure 7-5. The design strategy (similar to figure 6-33)

7.1.4 Selection

Testing theory in practice improves feedback on fit, relevance and workability of the theory. Still, as discussed in 7.1.1 there is limited control over the type, teams, clients and boundary conditions such as timeframe and budget, causing considerable research challenges. Within this research, the General Manager of Ulstein Sea of Solutions (USoS) decided to apply the methodology developed in chapter 6 in two projects (quote 7-1).

> *"Before the kick-off meeting our naval architect approached me, if Ties his work wouldn't be interesting for this project. I looked at it, embraced and presented it to the client."*

Quote 7-1. Managing director, Ulstein AXDS, USoS (translated from Dutch)

The projects were each commercial projects in the early stages of the design process, projects that are the core business of USoS:

1. Ulstein arctic drillship (AXDS), the Ulstein AXDS was developed by USoS during a feasibility study for the Norwegian oil company Statoil. Statoil hosted a design competition, where the designs of USoS and two other companies were evaluated.
2. Subsea Rock Installation (SRI) vessel, the Ulstein SRI-vessel was designed by USoS for the Dutch dredging company Van Oord.

The cases presented here provide insight in the consequences of implementing a methodology based on coevolving solutions and structuring the resulting interaction, to review if the model supports the four objectives set in 7.1.3 and to provide feedback on fit, relevance, workability and flexibility. The analysis is discussed in chapter 8. The boundary conditions of each project are discussed in more detail in the cross-case conclusions in section 7.4.

7.2 Ulstein Arctic Drillship (Ulstein AXDS)

The Ulstein AXDS was developed for a design competition initiated by Statoil, early 2013. Statoil selected Ulstein Sea of Solutions (USoS) as one of the companies, along with Gusto MSC and Inocean (Taraldsen, 2013) to design a turret-moored, ship shaped drilling unit capable of exploration drilling in harsh environments. Statoil selected USoS was because of their experience with drillship design and the Norwegian background of the Ulstein Group, of which the company is a part of. USoS identified that the designs available on the market did not suit Statoil's requirements and offered to develop a new, designated vessel for this particular project, applying the design strategy discussed in section 7.1.3. The approach resulted in the Ulstein AXDS design shown in figure 7-6.

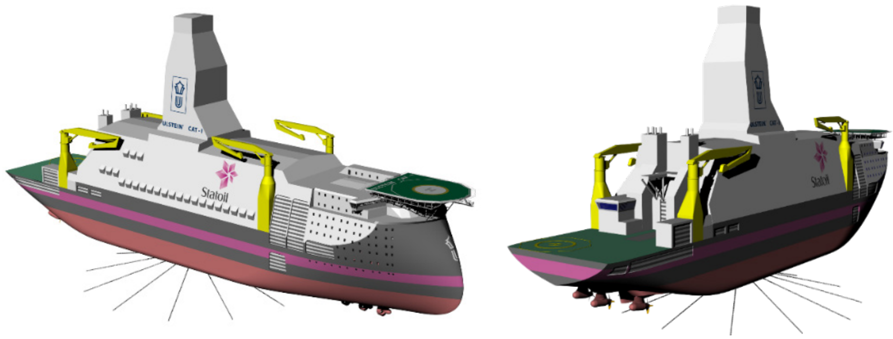


Figure 7-6. The resulting Ulstein AXDS design

The concept was designed with a broad set of technology partners. USoS cooperated with technology partners to develop the drilling equipment (2 companies), the turret (4 companies), electrical systems (2 companies), the shelter (1 company) and heating, ventilation and air-conditioning systems (1 company). Three companies, including a classification society, supported in evaluating the overall design. The dataset, summarized in table 7-2, is extensive and includes interviews, design and project management documentation.

Table 7-2. Dataset, experiment 1: Ulstein AXDS

Type	Amount
1. Interviews	12 interviews, 7h50m
2. Feedback on the design	1 file
3. Observations	26 files
4. Physical objects	5 files
5. Process documentation	47 files
6. Design documentation	3258 files
7. Project initiation documentation	71 files
8. Project management documentation	94 files

1. Interviews: After the presentation of the design in August 2013 twelve interviews were conducted with different project team members from the client, USoS and several technology partners. The interviews were done in an open manner to identify their experiences related to the structure of the project and the final design.
2. Feedback on the design: One of the planned interviews was cancelled, but the prospective interviewee provided written feedback on the design.
3. Observations: During the project personal observations were also documented in a personal journal.
4. Physical objects: The general arrangement and concept design report provided the final result of the project; the physical object.

5. Process documentation: The design strategy has been described in a separate set of documents and shared with the technology partners. The documentation provided insight in the development of the process for this specific project.
6. Design documentation: The design documentation contains all the documents and files part of the project, including deliverables, calculations, memos and different communiqués.
7. Project initiation documentation: The project initiation documentation contains all the information from the sales phase, the documents required before the project is officially started.
8. Project management documentation: The project management documentation identifies the contracts, hours and budgets in the project.

During the project I was involved as a researcher/practitioner, amongst others I contributed in developing documentation and calculations as a naval architect, as well as the appointed design process guardian (figure 7-7).

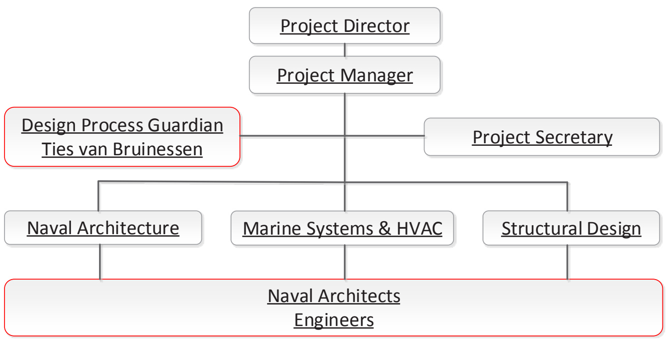


Figure 7-7. Project organisation (Ulstein Sea of Solutions, 2013)

Although the design was well-received by the client, another design was selected by Statoil for further development (Inocean, 2013). For USoS, the development of the Ulstein AXDS project continued with another client in subsequent projects. These developments are not discussed as they are outside the scope of this research. The following sections discuss both the development of the design (7.2.1) and observations related to the design and organisation by different involved actors (7.2.2).

7.2.2 Development of the Ulstein AXDS

The Ulstein AXDS has been developed over a period of 25 weeks between the kick-off meeting in mid-February 2013 and the final presentations for Statoil in early August 2013. Seven stages are recognized in the development of the Ulstein AXDS, this section illustrates five phases: the first phase (sales) is not discussed as it was not influenced by the theory described in section 7.1, the final section is not discussed because during the aftercare no further design steps were taken. The remaining stages are discussed in more detail in the subsequent paragraphs (figure 7-8).

Figure 7-8. Development phases of the Ulstein AXDS

The project officially started mid-February 2013. The project initiation concentrated on selecting the design strategy and the definition of the ship function: steps 1 and 2 of the design strategy. This was also the moment we presented design strategy to the involved actors. During the early stages Statoil made clear that the recent designs available to Statoil did not comply with the requirements they set for their business case: a commercial attractive vessel with high health & safety standards, low environmental impact and capable of exploration drilling in an Arctic environment. Based on these comments USoS decided not to offer a design based on their own Ulstein XDS3600 (figure 7-9), a deep water drillship developed previously, but offered to develop a new design for Statoil.

Figure 7-9. The Ulstein XDS3600

The design strategy developed in chapter 6 is applied during the development of this vessel. The design-strategy was based on the model available early 2013. This representation of the design strategy correlates with the 6 steps represented in figure 7-5, although the visualization is different (figure 7-10).

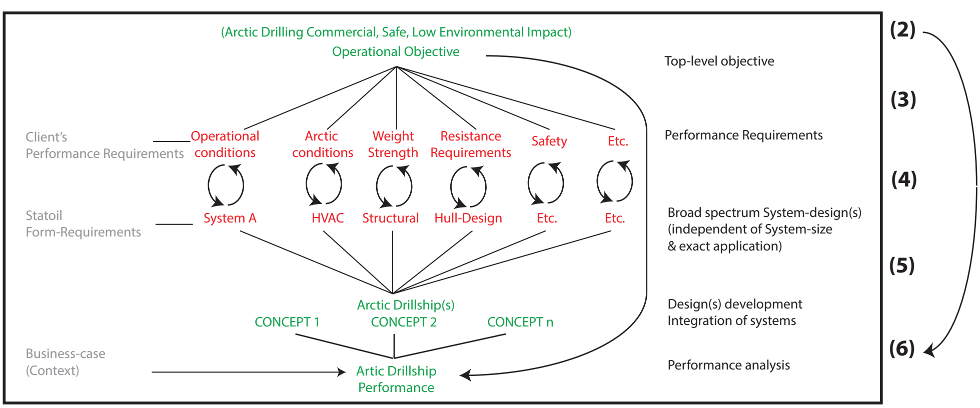


Figure 7-10. Representation of the UDP for the first experiment

The approach was uncommon for the offshore industry, as they are used to develop a design based on an existing vessel. In this case, specific developments occurred before the development of a new vessel, supporting the overall objectives, an approach which was considered new for the industry. Although the model and methodology discussed in chapter 6 is based on projects observed in practice, but there were still concerns if such an approach was applicable in this fast-track project (quote 7-2). However, during the initial presentations both the client's project team and the USoS management responded positive and the decision to apply this process was made.

> *"I would have to say, I was wondering in the beginning; are we taking on a fast-track project with a large, extensive method, is this the correct project to start such an approach. But at the end I think that the approach was suitable, and that we developed a good result."*

Quote 7-2. Project director, Ulstein AXDS, USoS (translated from Dutch)

The proposed design strategy is a departure from the approach common in the design of drilling vessels. During the start of the project some involved partners were worried that USoS would not been able to develop specific concepts based on this theory within the timeframe of the project (quote 7-3).

> *"We felt a little bit uncomfortable, we were wondering if it would be possible to come up with specific solutions, but the client said that they were comfortable that you would come with specific concepts, and that you had qualified, traditional engineers on board."*

Quote 7-3. Project manager, Ulstein AXDS, equipment manufacturer 1

Based on the overall ship objective the initial system boundaries (table 7-3) were defined by the USoS product director, project manager and lead naval architect, supporting the client's requirements. This correlated with step 3 of the process, where sets of performance parameters were used to start the development of specific systems with the necessary technology partners. The selection of the systems aimed to add relevant and expectedly complex systems in the development, without limiting to specialities. In several cases, the systems definitions were based on elements where the involved actors expected major changes, in other cases, such as the turret & mooring system, the client's requirement mentioned specific developments. These initial system boundaries provided the basis for each system development, furthermore it also provided insight which technology partners were necessary for each development.

The system definitions were used to allocate technology partners to each development and workshops were organized to remove the discomfort for several of them. The workshops provided insight in the design strategy and initiated their developments. Not all developments based on the system definitions went smoothly: limited experience with the approach and, in some cases, the reluctant attitude towards the new approach made it difficult to initiate system developments. The first phase from mid-February to mid-March focussed on starting individual projects. Besides kick-off meetings and finalizing contracts this also included developing the documentation to explain the design strategy, the system boundary development and the workshops.

Table 7-3. Initial system definition of the Ulstein AXDS

	Systems:	Involved companies
1.1	Hull Shape	internal
1.2	Electrical & Instrumentation	2 technology partners
1.3	Dynamic Positioning	internal
1.4	Heating, Ventilation and Air-conditioning	1 technology partner
1.5	Winterization Shelter	1 technology partner
1.6	Turret & Mooring	4 technology partners
	Drilling Systems:	
1.7	BOP & X'mas Tree Handling	2 drilling-equipment manufacturers
1.8	Drill Floor & Derrick related	"
1.9	Riser and Drill-pipe handling	"
1.10	Mud & Cutting Handling	"

The next two phases: the start-up and the system development concentrated on the individual developments in collaboration with the different technology partners (table 7-3), step 4 in the design strategy. Following the approach, there was no General Arrangement available during these stages; the different technology partners developed solutions for sets of performance requirements, complementary to the vessels objectives. The start-up differed over the 10 systems visualized in table 7-3. The USoS project team postponed several developments (such as the electrical & instrumentation), prioritizing others (such as the turret & mooring) to allow more time for more complex systems. The response to the approach and the available information also differed for each technology partner: some technology partners were happy with the available information (quote 7-4), while others lamented the lack of the general arrangement (quote 7-5).

> *"Usually, after the kick-off we have a couple of weeks or months related to defining the correct requirements. In this case, it was very clear from the start; how the project would go, the conceptual idea etc. making it possible to develop our own things."*

Quote 7-4. Project manager, Ulstein AXDS, technology partner (translated from Dutch)

> *"I can tell you, that both in the topside contractors and our own project team, there was concern: "I haven't seen anything", "where are the drawings", "what is happening". But I believed this was the way to do it, and I think I encouraged the others to believe that as well."*

Quote 7-5. Project manager, Ulstein AXDS, Statoil

After the start-up the technology partners started to develop individual solutions within their respective system boundaries. This phase was especially challenging for the project team at USoS: they were dependent on the technology partners for progress while the general arrangement was not yet under development, with only limited information was available on the overall ship design. Balancing the information provided to the technology partners between providing direction (increasing relevancy) and constraining the developments (reducing creative space) proved to be difficult (quote 7-6). Some rough sketches and initial sizing was sent to improve and clarify discussions. Still, throughout the system development the general arrangement was not provided.

> *"That the one who is drawing the vessel doesn't think he is working on a circular vessel, while the one who designs the mooring system, thinks he is working on a slender mono-hull; that is something you need to clarify in the beginning."*

Quote 7-6. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

The system designs provided insight in a wide range of subjects, from icebreaking features and thruster evaluation, to multiple concepts for the turret (figure 7-11). The number of concepts developed and evaluated was different for each technology partner, some were more accustomed to this type of assignments and developed and analysed multiple concepts (especially for the shelter and the turret), while others opted to use a single, conventional layout.

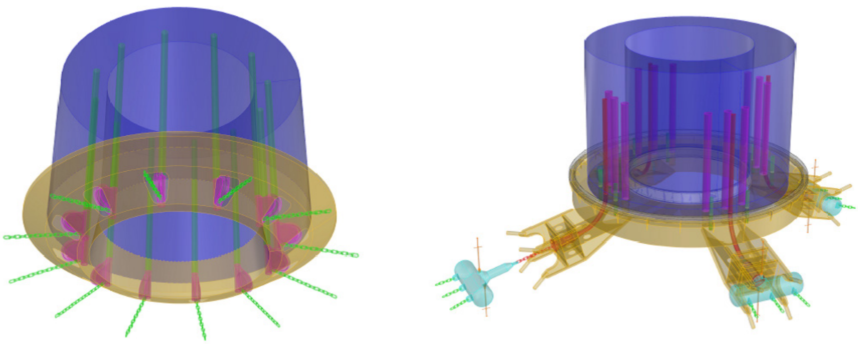


Figure 7-11. Vessel mounted turret (left), vessel mounted, spider buoy turret (right)

During the system developments the original boundaries had minor modifications: an 11th system was added: marine systems, which was not included previously but had considerable influence on the environmental impact and logistics in the vessel. Furthermore, the drilling systems identified earlier (system 1.7-1.10) were effectively handled, managed and developed as a single system. Still, the way the original boundaries were defined, without physical limitations, proved to provide sufficient opportunity to develop different solutions within these boundaries.

By the end of May the first draft of the vessel was developed, integrating the developments of individual systems (step 5 of the design strategy). During the integration phase the overall layout was determined, at this stage the performance of the individual systems was made project specific. The integration included an icebreaking hull, a combination of steel and composite for the shelter and the two different drilling systems. During the developments the technology partners and the naval architects cooperated actively, discussing the consequences of integrating their solutions and providing feedback on the flexibility of the developed solutions.

The integrated design was reviewed and evaluated (step 6 of the design strategy): amongst others on safety, costs and operability in the harsh environments, as identified by Statoil. The evaluation and documentation of the design was developed from mid-June to early August 2013, after which the design and the related results were presented to the Statoil project team and to several invitees, including potential operators. The client mentioned that compared to the conventional approach used by our competitors, the evaluation and the delivery of the documentation of the integrated design was relatively late in the project. This made it difficult for the client to review all documents (quote 7-7).

"Before you started delivering, I was already familiar with the other contractor's documents, their processes. From your company, I knew nothing, until I got the first documents, and then you sent over 100 documents in!"

Quote 7-7. Project team member 4, Ulstein AXDS, Statoil

7.2.2 Evaluation of the technical and organizational results

To identify the experiences of different involved actors interviews were conducted after the end of the project (table 7-2, 1). The interviews included team members from the Statoil, USoS and key personnel from different technology partners. The interviews concentrated on the design strategy, the actual design and the interaction between different actors. The following paragraphs summarize the conclusions of these interviews, split between the technical and organisational results.

Technical results: The Ulstein AXDS design was considered innovative by both the client and the involved technology partners. It incorporated a wide range of developments new to the offshore industry (quote 7-8), including the turret, the shelter and the integration into the overall solution. Although the design was developed by a group of naval architects with experience in the field, the design was different compared to designs they previously worked on (quote 7-9).

"I think your company is very innovative, that is also the feedback that we got from our discipline leaders."

Quote 7-8. Project team member 3, Ulstein AXDS, Statoil

"That was the feedback that we got from our client: there was a lot of innovation in the design, we developed something different than when we would have started with an example vessel, and modified that."

Quote 7-9. Managing director, Ulstein AXDS, USoS (translated from Dutch)

The vessel was not based solely on innovative solutions, the components applied in the design were in general based on known technology. This ensured that the vessel was both innovative and commercially attractive. Although the vessel is not (yet) in production, several actors mentioned that the design would provide a good starting point for the next phase. The design contained no showstoppers even though this design was developed from scratch, unlike that of our competitors (quote 7-10). When the project started, several actors worried that the open, creative design of the systems would result in infeasible, radical and out-of-the box solutions (as illustrated in 7.2.1). Eventually, the interviewees considered the final design containing reasonable, acceptable solutions for the industry (quote 7-11).

> *"I would say that your result would have been a very good starting point for the next phase."*
>
> *"I heard from your client that both your and one of your competitors solutions contained no showstoppers; I don't know if you received this feedback."*

Quote 7-10. First: project manager, Ulstein AXDS, equipment manufacturer 1. second: technical advisor, Ulstein AXDS, potential operator

> *"You presented reasonable solutions, not just purely out of the box solutions."*

Quote 7-11. Project team member 3, Ulstein AXDS, Statoil

During some system developments the choice between different solutions proved to be difficult for USoS, as operational considerations needed to be taken into account. In these systems multiple options and their considerations were shared with the client to avoid making a selection based on an incomplete set of information. Although with the best of intentions this was not seen as an advantage, as the design did not appear as matured as it was and should be (quote 7-12).

> *"You had two options: it was open and you left it up to the client, I think they were unsure which concept you were behind. You were playing two cards at the same time!"*

Quote 7-12. Technical advisor, Ulstein AXDS, potential operator

The initial system boundaries (table 7-3) were based on the experience of the USoS project team and the client's requirements, aiming to capture the developments required for this vessel. In the initial phases the system boundaries appeared to be useful and correct, guiding the involvement of technology partners and supporting the development of creative solutions. During the final phases, there were doubts if the initial subdivision was correct (quote 7-13).

> *"I think it was a very arbitrary subdivision [in system boundaries] that appeared correct when we started. Still, after 1.5 months we came to the conclusion that it wasn't the correct subdivision in ship's systems."*

Quote 7-13. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

Based on the observations during this project, the development of (initial) system boundaries proves to be very complex. During a recent MSc thesis the initial system boundaries and the eventual design were analysed using network theory (Killaars, 2014). This provided some insight in the way boundaries were developed, however, it was not able to define more successful boundaries or a 'better' architecture. Further research may result in improving the initial definition of these boundaries.

Organisational results: The interviewees also provided feedback about the organisation of the project: the technical and social interaction. In general, the design approach (figure 7-10) increased the creative freedom of the naval architects and the technology partners (quote 7-14). The approach did require a more proactive approach from technology partners, to develop their own solutions. Such an approach, with increased uncertainty, was something some technology partners were not used to, as in the offshore industry it is more common to develop equipment for existing designs (quote 7-15).

> *"We had the freedom to make things easier, we did not constrain ourselves, and that really worked: in our office, not with our technology partners."*
>
> *"I think it [the process] is not only very liberating, but also a necessity."*

Quote 7-14. First: naval architect, Ulstein AXDS, USoS. second: project manager, Ulstein AXDS, technology partner (both translated from Dutch)

> *"I was expecting that they [the technology partners] would be challenged to show this knowledge and use it to develop and improve something."*

Quote 7-15. Managing director, Ulstein AXDS, USoS (translated from Dutch)

Several technology partners saw this as an opportunity to develop new concepts and implement them in large offshore vessels, others were more reluctant and preferred minor changes to existing designs. The approach assumes that technology partners are willing to develop new concepts and showcase their knowledge (quote 7-15). This project proved that this is not always the case (quote 7-16). In some cases, they like to stick to the way they do things.

> *"I think I was a little bit naïve in that, because we like the way we work, we know what we do, and we are used to it."*

Quote 7-16. Managing director, Ulstein AXDS, USoS (translated from Dutch)

During the interviews, it became clear that several involved actors were worried about the maturity of the design approach, before implementing such an approach in practice (quote 7-17). This was reflected during the follow-up after the workshops (quote 7-18) and the request to further develop guidelines to support the conceptual developments (quote 7-19). These comments were valid, as both the methodology were developed further during the project, and had not been documented yet as thoroughly as it is done within this PhD dissertation.

> *"I got to know the process, and got to know what you were doing, that made it better. I think it's a good process, but maybe it should be more matured.*

Quote 7-17. Project team member 4, Ulstein AXDS, Statoil

> *"I think a little bit more effort could be put in to make it easier for you. You had a good presentation, it would be good to follow up on that presentation."*

Quote 7-18. Project manager, Ulstein AXDS, Statoil

> *"I expect that you get different results, if you use this design approach as a guide-line, and develop this 2 or 3 times, because you get more knowledge about the design freedom, and you start using that. If you use the approach for the 4th time, then you think: can we do something completely different, with the same functionality but an overall improvement? Perhaps!"*

Quote 7-19. Project director, Ulstein AXDS, USoS (translated from Dutch)

The design strategy had unmistakable effect on the interaction between the naval architect, technology partners and the client. The lack of a general arrangement (GA) played an important role in changing this interaction: this made it challenging to review the progress of USoS for the client, but also required a different approach to develop equipment (quote 7-20).

> *"One of the difficult aspects is that we didn't have a general arrangement, but we communicated that throughout the project. To the client, that's a risk; when you are working for 3-4 months, he hasn't seen a GA. To the client's feel, that is difficult to manage, to check."*
>
> *"The conventional approach is to get a General Arrangement, and they just fit their equipment in."*

Quote 7-20. First: managing director, Ulstein AXDS, USoS (translated from Dutch). second: project team member 3, Ulstein AXDS, Statoil

Finally, members of the USoS project team mentioned that the process is suitable for the early stages of design but cannot be applied to later stages of these projects, as the process aims to develop conceptual, innovative solutions with major impact on two levels of decomposition. During later stages this is not preferable, as this would result in major iterations. Furthermore, the approach improved argumentation, compared to a design based on a vessel from the Ulstein portfolio (quote 7-21).

> *"I think it is good to say that the approach, with its focus on specific design aspects, is very suitable for the feasibility phase, and partly for the concept phase. During these phases you want to determine the potential of a design, and then you have to look at certain aspects."*
>
> *"One other advantage of this process is that you can develop the argumentation, more than we do when we develop a conventional design. I think choices were well supported with both advantages and disadvantages, especially compared to a normal concept or basic design."*

Quote 7-21. First: project manager, Ulstein AXDS, USoS. second: project director, Ulstein AXDS, USoS (both translated from Dutch)

The approach was applied to identify potential innovative solutions and develop them, independently, with the necessary partners. The vessel integrated several creative solutions, without resulting in radical or infeasible solutions. During and after the project different actors discussed the maturity of the ship design and the maturity of the design strategy, valid comments which are necessary to take into account in further developments. Interestingly, many comments (for example quote 7-5 and quote 7-16) were not related to the content of this project or the content (the technical dimension) of the interaction, but focussed on the social part of the interaction. How actors interacted and how they perceived such a process changed considerably compared to more common design strategies in the industry (quote 7-15, quote 7-16).

7.3 Subsea Rock Installation (SRI) vessel

The Van Oord Bravenes (figure 7-12) was developed for the Dutch dredging company Van Oord as a designated SRI-vessel. The concept was made by the Dutch branch of the Ulstein Group, which includes Ulstein Sea of Solutions (USoS), responsible for the ship design and Ulstein Idea Equipment Solutions (UIES), responsible for the mission equipment.

Figure 7-12. The Van Oord Bravenes (van Oord, 2014)

Based on the positive response of the client and other actors involved in the first project USoS decided to apply the same approach in this project. Similar to the previous experiment, the design strategy developed in chapter 6 was applied in practice to determine if practice benefits from this design strategy; if it improves control while retaining the capability to develop innovative designs. In this project, I was not involved; the first experiment was a hands-on activity, this project was only influenced by the implementation of the design strategy, reducing my impact. The design strategy was provided by means of the design philosophy documentation of the previous experiment. The project managers presented key elements of the design strategy during the kick-off and implemented the visualizations in their project execution plan.

The concept was designed with several technology partners. UIES led the project, supported by USoS for the ship design. Different technology partners provided UIES with input on skidding, apron feeders, cranes, chains and bulk handling equipment. USoS was supported by technology partners involved in ergonomics and classification. The dataset of this project is extensive and includes interviews, project management data and design data from both UIES and USoS (table 7-4).

Table 7-4. Dataset, experiment 2: SRI-Vessel

Type	Amount
1. Interviews	4 interviews, 2h42min
2. Physical objects	20 files
3. Design documentation (USoS)	2374 files
4. Design documentation (UIES)	2158 files
5. Project initiation documentation	5 files
6. Project management documentation	154 files

1. Interviews: Four interviews were conducted with the project managers from USoS, IDEA and Van Oord after the contract for the basic design was signed, complemented with an interview with the involved naval architects. The interviews were conducted in an open manner to identify the experiences related to the project structure.

2. Physical objects: The general arrangement and the concept design report provided the result of the project; the physical objects.
3. Design documentation (USoS): The design documentation contains all the documents that are part of the design project including deliverables, calculations and communiqués.
4. Design documentation (UIES): The USoS design documentation is complemented with the design documentation of UIES. This contains all the documents part of the mission equipment design, including deliverables, calculations and communiqués.
5. Project initiation documentation: The project initiation documentation contains documentation related to the sales phase, the documents required before the project officially started.
6. Project management documentation: The PM documentation provides all the contractual, hours and budget documentation in the project.

The case study described here is not based on my personal observations, but on the dataset described above. After the concept design, the vessel was developed further, which resulted in a shipbuilding contract with Sinopacific Shipbuilding Group Shanghai, who plans to deliver the vessel to Van Oord at the end of 2016 (van Oord, 2014). The development of the vessel and the evaluation of both the technical and organisational results are discussed in the following sections.

7.3.1 Development of the SRI-Vessel

The SRI-vessel for Van Oord was developed in 21 weeks, from the kick-off meeting (end of May 2013) until the delivery of the final concept design report (mid-November 2013). Six stages are identified during the development of this vessel, the final stage of the project which includes the tendering process, the basic design and the contract signing is not discussed, as these activities are not considered to be part of the conceptual design. The remaining stages are discussed in the subsequent paragraphs (figure 7-13).

Figure 7-13. Development of the SRI-vessel

The project was officially kicked-off at the end of May. Before that, occurred during the project initiation and sales phase. During these phases, step 1 and 2 (the selection of the coevolving levels of decomposition and the determination of the ship function) were conducted. Before the project was offered to Ulstein, Van Oord determined that they wanted to make a considerable improvement to the design of Subsea Rock Installation vessel. To make this possible the project was not developed as a conversion of a bulk carrier design (similar to their fleet), but the project was offered to Ulstein to develop an integrated offshore vessel with a strong focus on the mission equipment. Based on the previous experiences the USoS management proposed to use the Ulstein Design Process (UDP), for this project, for this application visualized as figure 7-14.

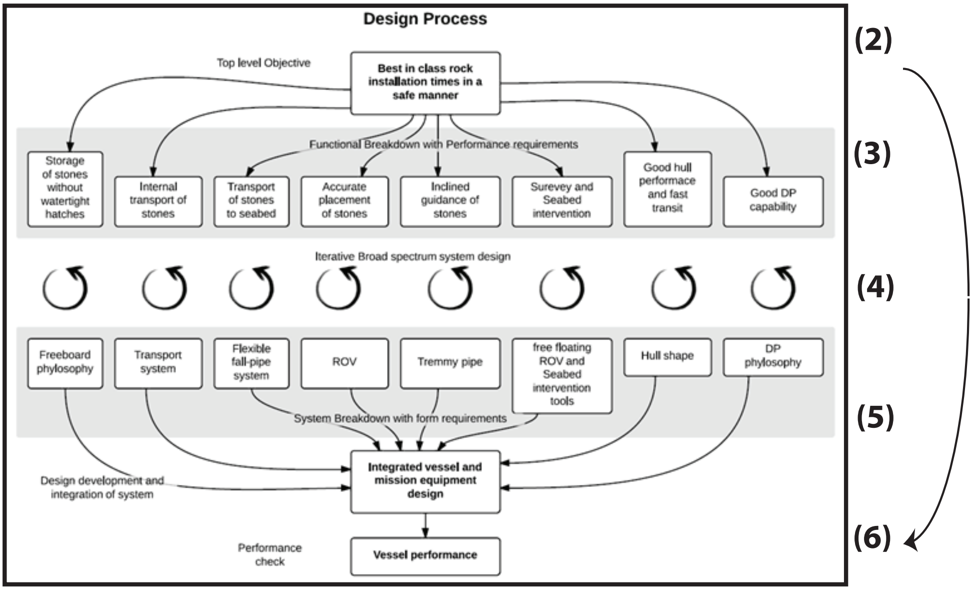


Figure 7-14. Representation of the UDP for the 2nd experiment

Based on the experience of the involved actors and the client requirements eight systems were identified as 'development areas' for this design (table 7-5). The majority of the systems (2-6) were the responsibility of UIES, who took the lead in the project. This correlated with step 3 of the strategy.

Table 7-5. Initial system definition of the SRI vessel

Systems:	
1	Freeboard Philosophy
2	Transport System
3	Flexible fall-pipe system
4	ROV
5	Tremmy pipe
6	free-floating ROV and seabed intervention tools
7	Hull shape
8	DP philosophy
Red: USoS responsibility	
Black: UIES responsibility	

The design strategy (figure 7-14) and the initial system definitions (table 7-5) were presented during the kick-off meeting and documented in the Minutes of Meeting (MoM) and the Project Execution Plan (PEP). During the kick-off meeting the involved actors agreed to use a light version of the approach applied in the Ulstein AXDS, a similar approach however with less systems.

The initial system definition and individual system developments started after the project team's first meeting early June and early July. During this stage, solutions to individual systems were developed (step 4). USoS concentrated on the freeboard philosophy, a development looking at different midship cross sections to improve operability of the vessel in collaboration with classification societies and flag state. UIES started working on the mission equipment, in particular on the fall-pipe system. To design the fall-pipe system, a further subdivision was made following a similar approach to identify the ships systems (table 7-6). Adding an additional level of decomposition did not have the effect UIES expected, as the components were often selected from existing designs (quote 7-22) and the focus remained on the integrated design (quote 7-23).

Table 7-6. Development of the flexible fall-pipe system into components.

3.1	Fall pipe configuration
3.2	Bucket storage frame and manipulators
3.3	ROV
3.4	moonpool frame
3.5	Buckets to ROV coupler system
3.6	Bottom steel buckets with chain and telescopic pipe
3.7	Tower Skid Arrangement
3.8	ROV and free flying ROV
3.9	ROV add-on tools.

"There was an existing system that the client uses, and that has been an important guideline for several design choices, well, we tried to maintain the facets that were working well."

Quote 7-22. Project manager, Van Oord SRI vessel, UIES (translated from Dutch)

"I think to describe what happened in this subdivision [the subdivision of the flexible fall-pipe system], that it's difficult to keep these problem areas separate; I noticed that, during the process, things continuously merge, because we were looking at the optimal cooperation between components, instead of optimizing different aspects."

Quote 7-23. Project manager, Van Oord SRI vessel, UIES (translated from Dutch)

The remaining systems such as the dynamic positioning (DP) layout, the other mission equipment and the hull selection were developed in parallel, but with less priority than the other systems. These systems were in general based on existing components, with less innovative items. The system designs provided the basis for the integration into a ship design in July/August (step 5). During this phase, additional naval architects were involved from USoS; the work in the previous phases was primarily done by the project managers. During this phase, the design was drafted and evaluated (quote 7-24).

"There was a rough layout available how the vessel should look like: the main dimensions, the hold, were given. We engineered the vessel around this setup."

Quote 7-24. Naval architect 2, Van Oord SRI vessel, USoS (translated from Dutch)

The developed system solutions were provided to the naval architects, however, the reasoning behind these solutions was not (quote 7-25). The additional flexibility of the design was recognized by the naval architects involved in the integration, although the flexibility that was attributed to the considerable changes to the mission equipment and other developments (quote 7-24).

> *"Before we started, 6 weeks of research was already developed, based on that, they delivered a series of constraints. That means there was a very interesting meeting for the naval architects where these constraints were set. This meeting would give more feeling to the priorities of the constraints."*

Quote 7-25. Naval architect 2, Van Oord SRI vessel, USoS (translated from Dutch)

Van Oord concluded after the vessel design was presented that it complied with all requirements, but that the size and costs were too high for the business case (step 6). This initiated the development of several variants, modifying the initial concept by reducing beam, implementing high-tensile steel, increasing draft or increasing depth. The variations, in combination with the systems development, helped clarify what the consequences of the design decisions were (quote 7-26).

> *"Designing like this makes it, sometimes painfully, clear what kind of consequences the limitations have, and that was something they ran into at their internal client; they develop a wish list, but they don't see and understand the consequences."*

Quote 7-26. Project manager, Van Oord SRI vessel, USoS (translated from Dutch)

The variation study provided sufficient opportunity to reduce size and costs of the vessel by reducing width and length. This variant was eventually selected and a final concept package was developed, resulting in a coherent and consistent design report.

7.3.2 Evaluation of the technical and organizational results

Four interviews were conducted to identify experiences of the project managers of the client, USoS and UIES and the naval architects involved in the integration and evaluation of the design, after the basic design contract was signed and the conceptual development was finished. The interviews provided feedback on the design strategy, the final design and the organisation of the project. The following paragraphs summarize the observations of these interviews, split between technical and organisation results.

Technical results: The concept design of the Van Oord Bravenes resulted in a building contract with the Sinopacific Shipbuilding yard in Shanghai (van Oord, 2014). The design was considered innovative, albeit perceptions differed: the client called the design a break from the past (quote 7-27), while the USoS project manager described it as known systems, structured differently (quote 7-28). The UIES project manager identified several systems that were new to the SRI vessels (quote 7-29).

> *"It is truly a break with the past, It looks fundamentally different, It's the first DP3 vessel; it's the first vessel that actually came from a clean sheet, no it is definitely an innovation."*

Quote 7-27. Project manager, Van Oord SRI vessel, Van Oord (translated from Dutch)

> *"I don't think that the vessel is revolutionary. In my opinion the vessel consists of known systems, structured differently; I know that people call this innovation, but I don't have the feeling that we made a large leap in the ship-design, like we did in the tower design [the flexible fall pipe-system]."*

Quote 7-28. Project manager, Van Oord SRI vessel, USoS (translated from Dutch)

> *"The watertight subdivision, the fall-pipe installation, the system to connect the buckets and chains, the transport systems for the rock, these are all never used before on a fall-pipe rock installation vessel."*

Quote 7-29. Project manager, Van Oord SRI vessel, UIES (translated from Dutch)

The development of the individual systems (table 7-5) was considered a positive step (quote 7-30), as innovative systems could be developed separately while still integrating smoothly. The further development of the fall-pipe tower into components (table 7-6) proved to be difficult to develop separately, as they were continuously looking at the integrated solutions (quote 7-23). The UIES-project manager actively questioned if they defined too many 'components' within the fall-pipe tower and if this was necessary (quote 7-31).

> *"I think that both the fall-pipe and the watertight subdivision were developed separately, ant that this worked very well; we had discussions with the classification society, we optimized them separately, but they combined beautifully."*

Quote 7-30. Project manager, Van Oord SRI vessel, UIES (translated from Dutch)

> *"I think that, if you look at the tower [the flexible fall pipe-system], that we actually defined too many systems, too many functions. If we missed something; should have selected a system that we didn't? No, not really."*

Quote 7-31. Project manager, Van Oord SRI vessel, UIES (translated from Dutch)

Organisational results: The interviewees also commented on the organisation of the project. The client mentioned that the process was complementary to the objectives of the client as it focussed on the correct items first (quote 7-32). The USoS project manager wondered if a conventional approach, where an existing design is modified, would yield similar results as the items that needed creative developments were clear from the start (quote 7-33).

> *"I think, from the day we started, that we focussed on the correct items; of course you need the shipbuilding aspects to get the bulk of the costs clarified, I know that, but I think I preferred to have started even a year earlier with the rock-dumping installation, but that was just not possible."*

Quote 7-32. Project manager, Van Oord SRI vessel, Van Oord (translated from Dutch)

> *"I think that the project approach was the correct one for this client, but in this specific vessel, that all systems were clear enough, and that such an approach would be unnecessary; therefore I think that the results of both methods would be similar."*

Quote 7-33. Project manager, Van Oord SRI vessel, USoS (translated from Dutch)

Similar to the first experiment, the general arrangement of the vessel was not developed until later in the design process, providing for more design space in both system designs and during the creation of the arrangement. For the client, this posed no problem (quote 7-34). The naval architects involved in the integration suggested that making extensive modifications to a portfolio vessel (for example the Deepwater Enabler) would yield similar design freedom (quote 7-35).

> *"The client was very positive, we mentioned in the beginning that they wouldn't get a GA of the vessel until later in the project, but that was no problem what so ever."*

Quote 7-34. Project manager, Van Oord SRI vessel, UIES (translated from Dutch)

> *"You generate that freedom when you modify a Deepwater-enabler with engine rooms that shift from front to aft, you have new holds, the accommodation is reduced from 240 to 60. Eventually you end up with a new vessel, and that generates that freedom."*

Quote 7-35. Naval architect 1, Van Oord SRI vessel, USoS (translated from Dutch)

During the project the design strategy was applied without my influence. This project showed that the approach improved interaction with the client and resulted in a feasible and innovative solution for the challenges posed by the client. The project manager and the naval architects from USoS questioned if making extensive modifications to a portfolio vessel would have yielded similar results, as the area were innovations were expected were clear. Still, the project manager of USoS recognized the benefits of applying such a process (quote 7-36).

> *"It provides freedom that you don't need to bother with other systems; if you try to design a ship incorporating all systems, then it's very time-consuming because you are taking all potential parts and interactions into account. By focussing on one system, and solve the rest when we run into something, you can improve focus and speed."*

Quote 7-36. Project manager, Van Oord SRI vessel, USoS (translated from Dutch)

One of the additional observations interesting to this research was that applying the approach during further decomposition did not appear to have any benefits. This correlates with the assumption in the hypothesis in chapter 5: The design strategy applied in this experiment is developed do allow for coevolving solutions on two levels of decomposition, and not for coevolving solutions on more levels of decomposition.

7.4 Cross-case observations

The two experiments described in this chapter apply a methodology which is developed based on coevolving ship design and system design, developed in chapter 6. The application of the methodology in practice aims to improve control during the development of these innovative vessels. The vessels developed in the experiments are each large, complex and innovative ships developed in commercial projects. Although they were both different, there were some similarities and differences between the project parameters of the projects (table 7-7). Each project concentrated on the early design phases of a large, complex and innovative vessel. The vessels were developed for a combination of functionality (although a different functionality for each vessel) and commercial attractiveness. Both projects were developed within a limited timeframe; between 21 and 25 weeks.

Table 7-7. Comparing project parameters of the two projects and the reference case

	Ulstein AXDS	SRI - Vessel	Reference case: LWI - Vessel
Project stage	Feasibility Study	Concept Design	Feasibility Study
Client	Statoil	Van Oord	Statoil
Project type	Design Competition		Design Competition
Company	Ulstein Sea of Solutions	Ulstein Sea of Solutions	Ulstein Design & Solutions
Country	Netherlands	Netherlands	Norway
Object	Turret moored, ship-shaped drilling vessel	Subsea Rock Installation Vessel	Light Well Intervention vessel
Objective	Commercial attractive, high health & safety standards, low environmental impact, exploration drilling in Arctic environment	Innovative Subsea Rock Installation vessel, both in mission equipment as well as vessel design	Cost efficient, high operability Light Well Intervention vessel
Technology partners	2 companies involved via client 11 additional companies	2 companies involved via client 6 additional companies	5 companies involved via client, 3 additional companies
Project timeframe	25 weeks	21 weeks	24 weeks
Design process	Ulstein Design Proces (UDP)	Ulstein Design Proces (UDP)	No changes to usual approach
Involvement	Design Process Guardian & Naval Architect	Provided UDP	No involvement

Between the projects were also several differences: both the Ulstein AXDS and the LWI vessel were developed for Statoil in a design competition. The SRI-vessel was developed in a designated project for a different client. Both experiments were developed at Ulstein Sea of Solutions, a design firm located in the Netherlands, the reference case is developed by Ulstein Design & Solutions, also part of the Ulstein Group, but located in Norway. The main difference between each project is the interference of the researcher in each development: both projects at USoS applied the interaction-driven design strategy: the first intervention with my own involvement, the second with only limited interaction between me and the project team. The reference case was not influenced by this research.

Both projects applying the methodology resulted in designs which were considered innovative, yet without major showstoppers. The experiences of the different involved actors were positive, although the increased design freedom did challenge the technology partners. Throughout both projects the client's project teams were satisfied with progress and the developments, even though the general arrangement was postponed and considerable innovations were implemented. The approach appears to improve control in innovative ship design, without constraining creativity. The effect of the model are discussed in more detail in chapter 8.

Chapter 8

Review of controlling innovative design in practice

"Analysing the consequences of implementing a new methodology"

This chapter evaluates the two projects discussed in chapter 7, to determine the results of the interventions and provide a warranted assertion (figure 8-1) to evaluate the value of the theory for practice (8.1). The review is based on the final designs (8.2) and the process (8.3) before determining the effect of the methodology on practice (8.4). The final sections discuss the developed theory (8.5) and look at the effect of the social dimension of the interaction, which is not explored within this research at this stage, but appears to have a major impact (8.6) (figure 8-2).

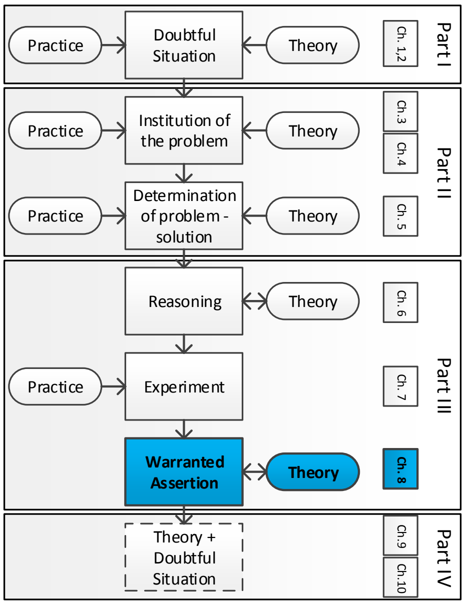


Figure 8-1. Overview of the research stages (equivalent to figure 2-6)

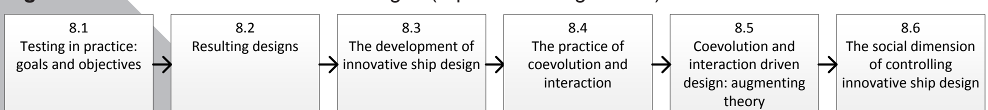


Figure 8-2. An overview of chapter 8

8.1 Testing in practice: goals and objectives

The experiments aimed to determine if describing a ship design process based on coevolving solutions and the related technical dimension of the interaction has value for practice. As practice is already capable of developing innovative designs, such a ship design strategy should aim to improve the objectives defined in section 6.1. To further evaluate the value of such a fledgling theory the fit, relevance, workability and flexibility (2.4) are summarized in subsection 8.1.2 and applied to evaluate the design.

8.1.1 Towards controlled, innovative ship design

To determine if the developed description has value for practice a design strategy is developed based on two coevolving levels of decomposition, following the cohesion in a system of systems to determine the content (or the technical dimension) of the interaction. Practice is already capable of developing innovative designs, but applying a description better suited to the industry may improve control during such projects. In section 6.1 this objective is developed into four sub-objectives, which are evaluated during the development of such complex objects:

1. Defining what may potentially result in innovative solutions
2. Structured involvement of technology partners and other actors
3. Support integration and coevolution within weak boundaries
4. The timing of creativity in design

These objectives were introduced in section 6.1 and used to evaluate the conceptual design strategy in 6.6.2. This chapter applies these objectives to evaluate the results from the experiments in section 8.4.1.

8.1.2 Evaluating fit, relevance, workability and flexibility

The evaluation of the results of a Deweyan Inquiry requires a different approach compared to a rationalistic research approach, which is evaluated using validation and verification. As proposed in chapter 2, newly developed theory during an explorative research should be evaluated on fit, relevance, workability and flexibility (Glaser & Strauss, 1967; Glaser, 1992).

The fit evaluates if the theory has suitable quality to meet the purpose of the developed theory. The relevancy determines if the theory provides an appropriate solution to the challenges seen in practice. The workability and flexibility provide insight in the applicability of the theory in supporting practitioners to generate results, while retaining the ability to be modified to cope with the changing practice. These four evaluating parameters are used to evaluate the results of the exploratory study in section 8.4.2.

8.2 Resulting designs

The designs developed in the three case studies are reviewed here, discussing the ship designs (8.2.1), system boundaries (8.2.2) and system designs (8.2.3).

8.2.1 Ship designs

The projects described in chapter 7 aimed to develop a new ship for a particular client. The designs are shown in figure 8-3: The Ulstein AXDS (experiment 1, 7.2) and the Van Oord Bravenes (experiment 2, 7.3).

Figure 8-3. The Ulstein AXDS (left), the Van Oord Bravenes (right)

The vessels were satisfactory for the respective clients: The Van Oord Bravenes is currently under construction with an expected delivery at the end of 2016, based on the design described in 7.3. The Ulstein AXDS was not selected for the subsequent phase by the client, but the vessel was developed further with one of the operators involved in the design review for their specific application.

The Ulstein AXDS and the Van Oord Bravenes developed using the interaction-driven design strategy are both considered very innovative. The Bravenes was described by the client as a ´break with the past' (quote 7-27). The Ulstein AXDS was described as the vessel with the most innovation compared to its competitors (quote 7-9). Still, both vessels were considered feasible and resulted in subsequent steps in the development. Developing design through a process that fosters innovation is not a guaranteed success, still, both experiments developed using the UDP resulted in designs that were considered innovative without containing major showstoppers.

8.2.2 System boundaries

Section 6.4.2 identified that system boundaries between the two decomposed system levels potentially play an important role in the development of new designs. The system boundaries developed within the two experiments were based on the experience of the involved actors such as naval architects and project managers. The system boundaries were not limited by physical boundaries, but by a set of performance parameters, allowing additional flexibility for system designers. Although the generation of the system boundaries was not influenced, they were documented in each project (table 8-1).

Table 8-1. Initial system definitions of the Ulstein AXDS (left) and the Van Oord Bravenes (right)

Ulstein AXDS: Systems	
1.1	Hull Shape
1.2	Electrical & Instrumentation
1.3	Dynamic Positioning
1.4	Heating, Ventilation and Air-conditioning
1.5	Winterization Shelter
1.6	Turret & Mooring
1.7	BOP & X'mas Tree Handling
1.8	Drill Floor & Derrick related
1.9	Riser and Drill-pipe handling
1.10	Mud & Cutting Handling

Van Oord Bravenes: Systems	
1	Freeboard Philosophy
2	Transport System
3	Flexible fall-pipe system
4	ROV
5	Tremmy pipe
6	free-floating ROV and seabed intervention tools
7	Hull shape
8	DP philosophy

The initial system boundaries are used as a starting point for the conceptual development of both the Ulstein AXDS and the Van Oord Bravenes. In the case of the Ulstein AXDS the system definition aimed to include the entire ship (quote 8-1). Based on the experiences within the Ulstein AXDS, the second project aimed to define systems where innovative solutions were required, instead of encompassing the entire vessel. Based on the experiments it appears that limiting the definition of system boundaries to specifically target the potentially innovative elements would improve control of innovative ship design.

> *"We tried to cover the entire ship with all the 'system area's'; I think that is something that we wouldn't do anymore, based on our experiences"*

Quote 8-1. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

During the projects the initial system boundaries sufficiently flexible to enable system designers to develop new and innovative solutions. Still, boundaries were modified: in the first project a system was added (marine systems) and the four drilling systems were effectively handled as a single system (systems 1.7 to 1.10, table 8-1). This raised the question if the initial system definition was correct, as arbitrary as it was (quote 8-2) and how this subdivision could be reviewed throughout the project, especially as the role (and perception) of system boundaries change. Recent research by an MSc student (Killaars, 2014) showed that these system boundaries can be evaluated using network theory, which could enable designers to review the consequences and validity of the boundaries throughout the project.

> *"I think it was a very arbitrary subdivision that appeared correct when we started. Still, after 1.5 months we came to the conclusion that it wasn't the correct subdivision in ship's systems."*

Quote 8-2. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

Defining system boundaries plays an important role in the design process. These boundaries were developed by the involved actors, but was not guided or managed by the developed methodology. The design strategy identifies on which elements and when system boundaries are based, but does not prescribe how these systems are developed.

At this moment, no theoretical framework appears to describe this, in particular when system boundaries are new and creative. Further research in this area may provide insight in how these boundaries (implicitly or explicitly) are developed by the involved actors. The experiments showed that limiting initial systems definitions to systems that (may) lead to innovative, creative designs improves control. These designs will undoubtedly influence their own boundaries. Still, increasing knowledge about the generation of these boundaries is necessary.

8.2.3 System design

The applied design strategy is based on developments in both ship design and system design, allowing for coevolution of both and supporting the ensuing technical dimension of the interaction. The approach allowed for more design freedom for technology partners involved in the system design as the ship design was not defined yet. This was different to a design strategy based on an existing vessel, which only allows for developments within existing and known system boundaries. This section discusses the resulting system designs in the two projects.

To develop the individual systems naval architects were supported by different technology partners. During the experiments, the system developments were initiated based on a (limited) set of performance requirements, without access to a general arrangement. In the reference case the technology partners based their designs on the initial, physical interface set by the naval architects: a rectangle with a length and width on the main deck, a strong boundary (quote 5-7).

The naval architect involved in the reference case (section 5.3.3) already discussed the possibility to develop mission equipment earlier in the project, as this would have supported integration in the ship design (quote 8-3). This correlates with observations from the client's project manager in the development of the Van Oord Bravenes, who thought that the approach focussed on the correct system developments, but that he would have preferred developing the systems even earlier on (quote 8-4).

> *"There should have been a process looking at topside solutions before starting with integrating the solution. If a topside vendor would have started the project 6 months before us, we could actually have a possibility of an integrated, reliable, overall solution."*

Quote 8-3. Naval architect, Ulstein LWI-vessel, UDS

> *"I think, from the day we started, that we focussed on the correct items; of course you need the shipbuilding aspects to get the bulk of the costs clarified, I know that, but I think I preferred to have started even a year earlier with the rock-dumping installation, but that was just not possible."*

Quote 8-4. Manager product development, Van Oord SRI vessel, van Oord (translated from Dutch)

The design approach, allowing for parallel developments of the ship design and system design, appears to amplify the preferences of different involved actors. After the experiments an even more extreme approach is proposed (quote 8-3, quote 8-4): developing system designs without the ship design. Whether this would yield better results or that the extensive system knowledge would lead to surprises in the integration is not clear (quote 8-5).

> *"You need to find a balance between a certain design-depth in a system and to take the time to bring it all together in a ship-design, to avoid surprises."*

Quote 8-5. Project manager, Ulstein AXDS, USoS (translated from Dutch)

During the projects different technology partners were asked to develop solutions for a set of performance parameters, without the physical constraints usually provided in ship design. Not all technology partners were willing or capable in developing such new designs, as they were used to implement existing solutions. Still, in several cases the involved technology partners developed innovative solutions based on known components that have not been developed previously. Systems which included the tower on the Van Oord Bravenes or the turret and shelter on the Ulstein AXDS.

Still, USoS was a little bit naïve in their expectations (quote 7-16), during the experiments it became clear that company culture, personal experiences or interference from the management may limit creative developments. This was in contrast to other companies, which thrived when asked to develop new solutions, as they were able to showcase their capabilities.

8.3 The development of innovative ship design

The involved actors not only shared observations on the design, but also provided feedback about their perception of the design process. This included feedback on the design strategy (8.3.1), focus on two levels of decomposition (8.3.2), managing the technical dimension of interaction (8.3.3) and the argumentation related to design (8.3.4).

8.3.1 The role of the design strategy

The design strategy implemented during the experiments was uncommon in the offshore industry (quote 8-6). It explicitly defined how different actors should work together to develop innovative solutions in the early stages of the design process. The strategy resembled how some actors already worked (quote 8-7), or preferred to work (quote 7-14), but making this process explicit made it possible to align developments and activities between the client, ship designers, technology partners and other actors: a role of the strategy which was not anticipated.

> *"My first impression was that I really liked it, I liked the approach but I thought it was going to be a struggle; everybody likes to work the way they have always done and it's a challenge to try to change people, to have them think differently. Your approach required that you inspired people."*

Quote 8-6. Project team member 3, Ulstein AXDS, Statoil

> *"When we had the workshop: that clarified everything. It was the way we usually do this, but now we just document what we do."*

Quote 8-7. Layout designer, Ulstein AXDS, equipment manufacturer 2

Describing the design process had a positive effect on aligning the different actors in the project. Yet, in the first project, different actors made clear that the approach needed to mature: not only in documentation and terminology, but also in feedback. This is a particular valid comment at this stage, as the related research was still under development. USoS is currently in the process of developing the design strategy further to improve application in other projects (quote 8-8).

> *"At first, they were not used to working like this, secondly, we were not used in working like this. The principle of this much-discussed design procedure, here as well, was that we start to think about what the design problem actually is and how we can solve it as efficiently as possible."*

Quote 8-8. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

The design strategy applied to the Ulstein AXDS and the Van Oord Bravenes development is made for the early stages of the design process: the moment when conceptual designs ('concepts') are designed and implemented. This was also voiced by different actors (quote 7-21), who saw more applications as a possibility, but only within feasibility studies and the earlier phases in the conceptual design phase. In later phases the focus would be more on balancing, optimization and consolidation, then such an approach would be less suitable.

8.3.2 Focus on two coevolving levels of decomposition

The approach made explicit which conceptual developments on a ship design and system design level (section 6.4.2) were allowed. During the Van Oord Bravenes project UIES applied a similar approach to the fall-pipe tower (system 3, table 8-1): the system designers divided the tower into nine components, with the intention to develop these components separately (figure 8-4). This increased the development to three levels of decomposition (as described in 5.3.4, (4)) potentially resulting in major iterations. The involved project manager mentioned that working on three levels of decomposition did not yield the expected results: the involved team concentrated on the integrated solution (quote 7-23), while selecting components from existing solutions (quote 7-22) (figure 8-4). Although not definitive, this strengthens the hypothesis that to improve control in innovative ship design, the process should focus on two levels of decomposition.

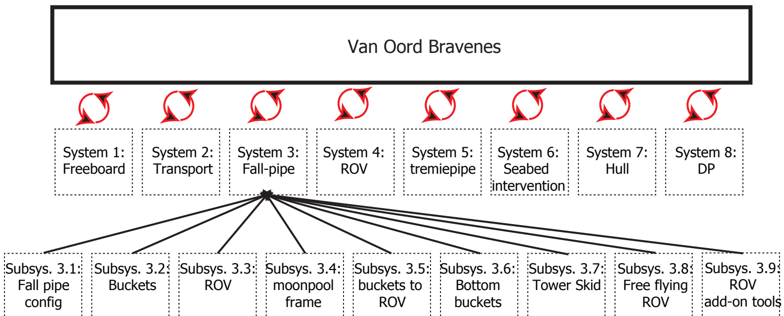


Figure 8-4. The coevolution between the ship design and systems in with existing solutions on a component level

The applied design strategy had an additional effect beyond the technical interaction between the ship design and system design. In both projects the client's project team was positive about and comfortable with the development throughout the project, even though key deliverables such as the general arrangement were delivered late (quote 7-32, quote 8-9). This in contrast to the reference case, where the relation between the teams of the client and UDS was strenuous in the early stages of the project (quote 8-10).

> *"The way Ulstein handled the project very professional; you took to the task, was very good in the interfaces, and when you saw that an interface was an issue, a challenge for the project, then you took responsibility, regardless if it was inside your scope."*

Quote 8-9. Project manager, Ulstein AXDS, Statoil

> *"I can only say that in the beginning of the project we were struggling in understanding how UDS developed the concept. It took some time before we saw the results from them, but after a while we understood that the way you dealt with the project and developed technical solutions was very good."*

Quote 8-10. Project manager, Ulstein LWI-vessel, Statoil

The approach appears to improve interaction between actors involved in ship design and system design, yet, applying the approach beyond these two levels does not appear to be successful. Interestingly, the application of the design strategy did have an effect beyond the two coevolving levels of decomposition it was designed for: it also improved the interaction with the client.

8.3.3 Managing the technical dimension of the interaction

The approach aimed to improve interaction using a (theoretical) model of the cohesion between two levels of decomposition. In this case, the cohesion beyond the original system boundaries played a role in two steps of the design strategy: the definition of sets of system performance parameters based on the vessel's functionality (step 3, figure 7-5) and the integration of the systems into an overall ship design (step 5, figure 7-5).

Step 3 provides the naval architects with initial system boundaries based on sets of performance parameters, which aim to complement the objectives of the vessel. These initial boundaries can be developed separately, where necessary with the support of technology partners, but they do not contain physical constraints or predefined solutions. In comparison, the industry is used to receive a predefined general arrangement where equipment is fitted in (quote 7-20). The response of the involved equipment manufacturers and designers differed, some partners preferred the set requirements; others would have preferred a more constrained assignment. The initial stages of this process did require more project management effort, mainly caused by technology partners who were not accustomed in working like this, and needed to be guided. During this stage only a limited amount of drawings and documentation were produced.

Step 5 concentrates on the integration of newly developed systems into an overall ship design. At this stage, naval architects were involved to integrate and implement these systems. The technology partners were expected to select the most applicable solution, but many felt uncomfortable in selecting a single solution. Eventually the involved naval architects selected and integrated the solutions (quote 8-11).

> *"To be certain that we had the correct solutions of each sector, we then made a selection which combination of techniques was implemented. I think that's what happened, while I expected that the technology partners would make that choice!"*

Quote 8-11. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

The integrated solution provided sufficient context to determine the characteristics of each system solution, making it possible to balance and evaluate the performance of both the ship design and the individual systems. During the Van Oord Bravenes project the integration was done by naval architects who were not involved in the earlier stages of the process. The selected solutions were provided, but the considerations related to the selection were not. For them, this caused a challenging situation, as they had to integrate without knowing the considerations, flexibility and requirements of certain system solutions, making it more difficult to create an integrated design taking all considerations into account.

The approach appears to improve the technical dimension of the interaction between two levels of decomposition: it supported and guided system designers without constraining the development of new concepts. Furthermore, the approach provided guidance while integrating new system design into the ship design. Still, special attention is required for the transfer of information when actors change throughout the project or when actors are reluctant or not capable of developing new concepts.

8.3.4 Argumentation throughout the design

The Ulstein AXDS (experiment 1) and the LWI-vessel (the reference project in section 5.3.3) were both developed for design competitions initiated by Statoil. The design competitions required additional argumentation why certain design choices were made throughout the design. The design strategy had an unexpected effect improving the required argumentation in the design process, as it required the different actors to document developments and decisions during this process (quote 7-21). Far more than when developed based on a conventional approach (quote 8-12).

> *"We were used to work on project, focussing on the solutions, not argumenting the solutions. We selected a solution, moved on, see if it works and then move further; now we had to argument everything."*

Quote 8-12. Naval architect, Ulstein LWI-vessel, UDS

Improving design arguments could be a considerable advantage over competitors in the offshore industry, an unexpected result of the strategy.

8.4 The practice of coevolution and interaction

The previous section discusses observations related to the final designs and the process of developing new and innovative ship designs during the two experiments and the reference case. This section explores the results of the experiments with regards to the objectives (8.4.1) and fit, relevance, workability and flexibility of the theory (8.4.2).

8.4.1 Improving control during innovative design

In the start of chapter 6 four objectives are identified that would improve control during the development of innovative ship designs. These four objectives provide insight if the developed and implemented procedure has value for practice during the development of innovative ship designs:

1. Defining what may potentially result in innovative solutions: During the experiments the decision which parts to focus on in innovative design (the ship design and systems design) was made early in the project. The projects showed that the system selection was key in determining which systems were allowed change beyond known solutions. In the first project the system selection aimed to encompass the entire vessel, in the second project only systems were defined that could potentially result in innovative solutions. The approach provides a good starting point, but limiting system definitions to only encompass the parts of the design that are allowed to develop into concepts would improve this even further.

2. Structured involvement of technology partners and other actors: The projects described in chapter 7 were each developed with a wide range of technology partners. Within both experiments, these partners supported the development of new systems (step 3, figure 7-5), but were also involved in evaluating the overall design (step 6, figure 7-5) to support the naval architect with additional knowledge. The technology partners had different roles: some were involved in analysing the overall design, others were involved in developing individual systems. Each played a role in the project, albeit a completely different one. The first role was expected: creating new systems to improve functionality based on a set of performance parameters. The second focussed on analysis, as innovative solutions change the current perspective on the market (Noble, 2012), requiring new theory, heuristics and rules of thumb (Smulders, 2014).

3. Support integration and coevolution within weak boundaries: The design strategy aims to develop system based on sets of performance parameters without adding physical constraints. These boundaries are less stringent than boundaries based on an existing design, which are usually well defined and physical. The boundaries within both experiments were relatively weak or conceptual, and allowed for considerable developments within and beyond these boundaries. Still, the integration into an overall design went smoothly in both experiments: The general arrangement was developed within a limited timeframe and included individual system developments. During the second project the importance of transferring the reasoning behind the individual system developments became even clearer; the involved naval architects mentioned they would have been capable to improve the integrated design, if reasoning behind the system selection was available.

4. The timing of creativity in design: The design strategy does not control creativity required to develop innovative solutions, yet it does try to improve the timing of developing creative solutions. The design strategy identifies two moments for creative developments: the system developments based on sets of required performances and the integration of these systems into a new ship design. The approach appears to improve the creative design, compared to a conventional ship design approach (quote 8-13).

> *"That is our conventional of way of working; the creative process within USoS only occurs during the first three days, when an experienced ship-designer develops the General Arrangement. As the GA was not available, multiple people had the possibility to develop all kinds of potential solutions, we were creative for 4 months, not just 3 days."*

Quote 8-13. Naval architect, Ulstein AXDS, USoS (translated from Dutch)

The observations in the experiments show additional moments where creativity plays an important role. The initial system boundary development (8.2.2) was a creative step, as the clustering of performance parameters is highly conceptual; at this stage it is unknown if these sets of parameters would yield potential results. Furthermore, the involvement of certain technology partners to evaluate the final designs, as seen in the different projects requires the development of new evaluation tools. This is also a creative step, as knowledge is required to test the innovative solutions. In coevolving solutions there appear to be not just two, but four moments of potential creativity: the system developments and the integration (step 4 and 5, figure 8-5, dark blue) but also the development of the system boundaries and the development of new tools to evaluate the ship design (step 3 and 6, figure 8-5, light blue). Each require different activities and, most likely, a different type of creativity, although further research is needed to pinpoint the different styles and their consequences.

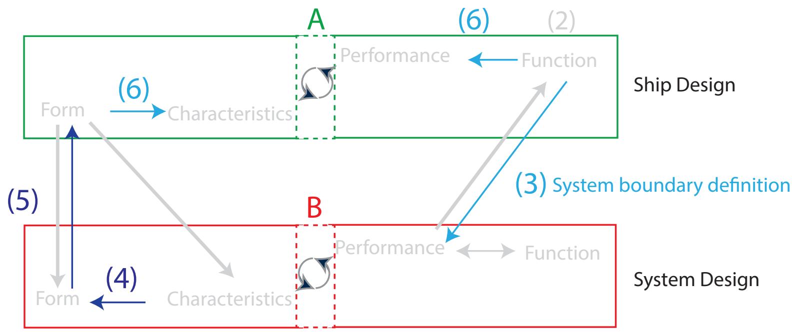


Figure 8-5. Creative steps in the design strategy

The four moments of creativity defined in the previous paragraph are initiated by the coevolving solutions, these are complementary to the development at each individual level of decomposition, in engineering design described as the coevolution of the problem solution (visualized in figure 8-5 by A and B). These creative steps are not contradictory, but complement each other.

Except for the planned elements, the approach also had effects beyond the initial phases: the involvement of technology partners in an early stage and the emphasis on the system developments resonated throughout the later stages of the project. During the integration, balancing and optimization stages, system designers feel responsible for their developments. This results in a different interaction compared to a situation when a solution from the existing portfolio is selected.

The objectives defined at the start of chapter 6 are covered and improved by the implemented design strategy based on coevolution and interaction. The different process introduced in chapter 6 and applied in chapter 7 seems not only to improve control in the design of innovative vessels for USoS, but also to identify areas where further research is necessary. Such research could include the different types of creativity, a more detailed analysis focussed on the content of the interactions and the social implications of applying such a design strategy.

8.4.2 Fit, relevance, workability and flexibility of the theory

To review the results of the Deweyan inquiry the developed theory is discussed in relation to fit, relevance, workability and flexibility.

1. Fit: This research aims to understand how large, complex and innovative vessels are developed by experienced ship designers. The theoretical developments of chapter 6, based on the observations from chapter 5 and tested in practice appear better suited to describe how ship designers work. When testing the further development of the model as an explicit design strategy the approach shows to focus on the items defined by the actors as the correct ones and result in innovative designs. The design strategy appears to make an approach already followed intuitively more explicit. Still, although it improved in practice, there were still considerable (social) effects that were not described by the model, these are discussed in more detail in chapter 9.

2. Relevance: The developed model appears to discuss a complex, but relevant problem: actors involved practice and theory expressed their interest. During both project the clients, represented by experienced project managers, responded positive to both the research and the design strategy. Furthermore, the results of this research are developed further at USoS with applications in several of their projects. Furthermore, as discussed in the previous section the four objectives defined at the start of the development are met which provides value for practice.

3. Workability: The result of this research is twofold. First of all, during the experiments the innovative designs were developed in the available timeframe and resulted in system and ship designs which were considered innovative by the client, without being unrealistic. The involved ship designers at USoS still apply the design strategy, currently named the 'Ulstein Design Process (UDP)' in different projects. Secondly, the developed theory is applied by the ship designers at USoS as a framework to question available theory and develop new tools or initiate additional research. The theoretical framework used as a template for the design strategy should be validated more, but even though it is still under development it provided the basis for a workable design strategy applied in practice.

4. Flexibility: The interaction-driven design strategy is based on the interaction between ship design and system design. However, as discussed in section 6.3.2, the model of cohesion the design strategy is based on should be able to describe the interaction on different levels of decomposition, or in other complex, large and innovative systems. This research concentrated on the ship design industry and is therefore limited in application, but further research may prove application in other industries.

The results of this research fit the initial challenges, provide relevant insight and a workable and flexible solution. Still, this is an exploratory research and should be explored further. The model could benefit from including the social dimension of the interaction, as this has considerable influence on the product development activities. To improve application of the theoretical model within different fields of research the model of cohesion has to be further developed, for example with respect to a more generic terminology and applications in other industries, to avoid a ship design centric approach.

8.5 Coevolution and interaction driven design: augmenting theory

This research aims to develop theory and practice in parallel, resulting in both changed practice and new theory. This section summarizes these developments and draws conclusions from applying this in practice. This section discusses the terms and conditions of applying such theory in practice (8.5.1), and discusses the observations which refine existing theory (8.5.2).

8.5.1 Applying new theory: terms and conditions

The design strategy applied within this research concentrates on the parallel development of the system designs and ship design. The model of cohesion this design strategy is based could be applied in more situations, as it provides a more generic overview of the cohesion and interaction in a system of systems.

The model can be applied when an innovative object is developed consisting of multiple levels of decomposition, involving different actors either in or outside a company. The model describes the cohesion between different levels of decomposition, independent of the project requirements. However, based on the requirements of each project a design strategy can be developed following this model. The methodology applied within this research is one example of such a design strategy, concentrating on coevolving ship and system design, starting from the objective of the vessel. But based on other requirements seen within this industry, projects can also be initiated based on a portfolio development, a set of characteristics or other even a rough sketch.

Dependent on the project a more extensive or more constrained approach could be applicable, in some cases only a limited number of systems could be interesting for innovative developments, in others a multiple innovative solutions are required to achieve a certain goal. This also relates to the available budget for each project; although a large number of system developments could be preferable, a selection has to be made to keep projects within time and budget.

As discussed before, the application of a design strategy not only impacts the technical dimension of the interaction (the content) but also influences the social dimension of the interaction. In some projects, applying such a strategy can have unexpected influence on the relationship with the client. At this stage, it is unclear what social considerations influence the design strategy, but elements such as thrust, character and culture are expected to play an important role.

8.5.2 Refining theory

The research aims add to theory and support practice by exploring how experienced ship designers develop innovative, large and complex vessels. An exploration of theory (chapter 3) and practice (chapter 4) show that during these developments solutions coevolved on multiple levels of decomposition, resulting in considerable interaction between the involved actors. Both coevolution and interaction only had limited descriptions in ship design theory (chapter 5).

To interpret these observations the technical dimension of the interaction (the content of the interaction between to system levels) was modelled by determining what influences the cohesion between an existing ship design and a single system design (figure 8-6, similar to figure 6-12). This model is used to develop a design strategy based on two coevolving solutions: allowing ship design and system design to coevolve (chapter 6).

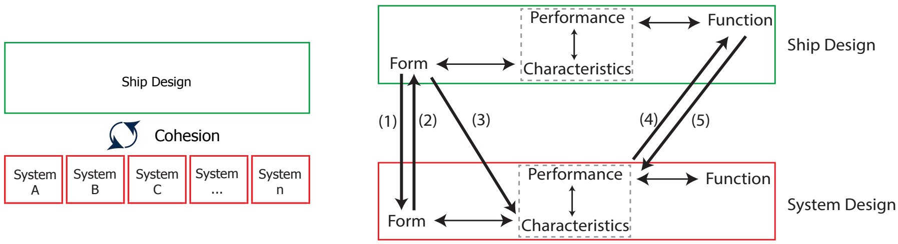


Figure 8-6. The cohesion between ship design and system design (similar to figure 6-12)

The theoretical model of the cohesion provides insight in the technical dimension of the interaction. To determine if the model had value in practice, a design strategy was developed and tested based on two coevolving levels of decomposition: ship design and system design. Current practice was already capable of developing innovative ships (chapter 4), therefore the value of implementing such an approach was to improve control during such processes. The design strategy developed in chapter 6 is applied in two projects at USoS.

The design strategy appears to improve control during the initial phases of these projects. Both projects resulted in both innovative design and successful projects. The experiments also showed that the social dimension of the interaction had considerable effect on the design, an effect that this model does not capture (8.3). Furthermore, testing the proposed shift in perspective used to describe ship design in practice resulted in a myriad of subjects that require further research, ranging from improving definitions, applications in a system of systems, to the different manifestations of creative activities (8.4).

The definition of coevolving solutions is complementary to the original definition of coevolving problem & solution as defined by engineering design research (5.2.2). In the original definition, the focus was on single objects, this is now further enrich with a perspective beyond the system boundaries, which can be applied in more complex system of systems (figure 8-7).

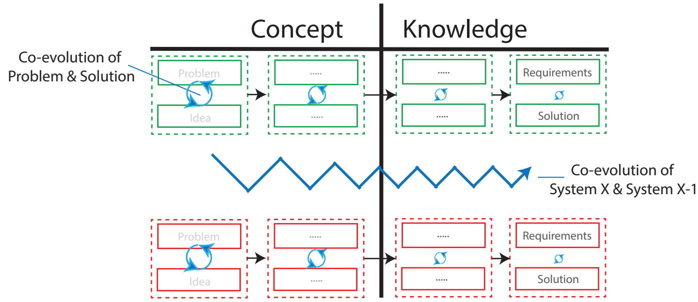


Figure 8-7. Coevolution of problem/solution complemented with coevolution of two levels of systems.

This research develops an initial model and a first methodology, but it does not provide a final, conclusive method for innovative ship design. To achieve this, a different type of research is required to validate and verify the original model, and to apply other design strategies. Such research could also be used to evaluate the quantitative consequences of applying different design strategies in multiple projects, evaluating parameters such as project time, required hours, costs and amount of rework in later stages. The main contribution to theory is the introduction of a new perspective on ship design, based on coevolution and interaction across the original system boundaries on at least two levels of decomposition. Such an approach proves more suitable in describing innovative ship design than conventional ship design theory.

8.6 The social dimension of controlling innovative ship design

From its first introduction in chapter 5 the social dimension continues to return as an important feature of controlling innovative ship design. The conclusions here are no exception: throughout this chapter observations point towards the social dimension of developing these innovative solutions. This social dimension provides an interesting starting point for further research. To accommodate this, the references related to the social dimension are collected and summarized in five main observations:

1. Perception differs: During the experiments it became clear that the perception of the actors involved in the design differed. This was also visible when evaluating innovation in the final designs (for example in 7.3.2) when different actors had a different perception on the innovations in the design. This also holds true for the system boundaries (8.2.2) because boundaries that are clear and offer innovation space for one actor can be constraining and limiting for another.

2. Not all companies are willing to develop innovative solutions: During the experiments it became clear that not all technology partners were willing or able to develop innovative solutions (8.2.3); although in general, companies are required to innovate to survive (chapter 1). Why companies and the involved team members were not willing to change their approach and designs was usually a combination of personal experiences, company strategy or cultural differences between and within companies. This could be the starting point for an interesting research.

3. Accepting a design strategy developing innovative solutions: In both projects the client, represented by the respective project managers, advocated the approach and provided positive feedback. The approach was primarily oriented on the interaction between the ship designer and system designers, but still had a pronounced effect in the interaction between the client and the ship designers. In the reference case, a more strenuous relation between the naval architects and the client's project manager was visible, especially during the early phases of the project (8.3.1), attributed to the lack of a clear design process. The role of the design strategy in the interaction with the client is not clear; it does not influence the content of the interaction, but it has considerable social implications.

4. Challenging how companies work, the social challenges of changing the design process: The design strategy applied in the experiments did not only influence the approach of the ship designers at USoS, but also required changes to how different technology partners developed their respective systems. Throughout the interventions, the additional focus on the technical dimension of the interaction amplified and polarized these interactions, for example by requesting more or limiting available information. This caused discomfort with the involved partners, questioning if it would lead to specific solutions or would be applicable to high-value projects such as the Ulstein AXDS (quote 7-2, quote 7-3 and quote 7-5). The social implications of such changes are considerable, but currently unexplored.

5. System developments matter: The design strategy concentrates on the early stages of the design process, yet it also had considerable effect on the later stages of the product development (8.4.1). It appeared that the approach, with its emphasis both on system design and ship design had a prolonged effect while optimizing and consolidating the design; activities that lay well beyond the initial stages of the development described in this research. This effect appears to originate from an additional responsibility for the design, a responsibility that rises beyond providing product leaflets and portfolio designs.

These initial observations illustrate the importance of the social dimension in these developments. Chapter 9 further explores this 'social dimension' as a new doubtful situation, with the aim of introducing and initiating further research on the subject.

Part IV

On the future of innovative ship design

Chapter 9

The social dimension of interaction

"Redefining the doubtful situation: a starting point for further research"

The social dimension of the interaction was identified as a factor in the development of large offshore vessels in chapter 5, but it became more and more pronounced throughout the subsequent chapters, which explored the technical dimension of the interaction as part of the coevolution process. This chapter reviews the social dimension of the interaction in more detail to define a new doubtful situation, a starting point for further research. This doubtful situation, combined with chapter 10, provides the conclusion for this dissertation (figure 9-1).

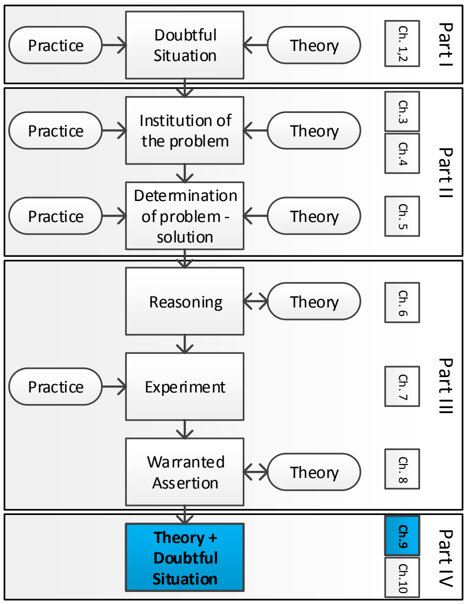


Figure 9-1. Overview of the research stages (equivalent to figure 2-6)

The observations related to the social dimension are discussed (9.1) before exploring the available theory (9.2-9.3) for research purposes. Subsequent sections discuss tools that may be used in such a research (9.4) and the benefits and challenges of exploring the social dimension in practice (9.5) before redefining the doubtful situation (9.6).

Figure 9-2. An overview of chapter 9

9.1 Observations from practice

Several of the observations in chapter 5 and 8 were not discussed by the model of the technical dimension of interaction. They are more related to the social dimension of the interaction and therefore require a different theoretical framework to explore. The two observations from chapter 5 and the five observations from chapter 8 are summarized below:

Chapter 5, observation 1. There is no guarantee for success in innovating: It is well known that not all creative and potentially innovative ideas result in a successful application; this means not all creative ideas result in innovation. However, this contradicts commercial practice, where profit, reducing risks and security play an important role. How this insecurity is handled during the process of innovating is influenced by the personal experiences and knowledge of the involved actors (and companies). Such approaches have a major influence on the development process.

Chapter 5, observation 2. The role of social interaction and knowledge in innovating: The process of innovating is dependent on a combination of creativity and knowledge of the involved actors. Yet, bringing both together proves to be a challenge. The interviewed leaders of industry (5.3.2) approached this differently, ranging from changing office layout, removing doors to improve communication, working with different cultures and shared design reviews. Each of these approaches appears to aim for a combination of knowledge and creativity to generate innovation with a strong focus on the social dimension of interacting actors.

Chapter 8, observation 1. Perception differs: The model and methodology developed in chapter 6 concentrates on the content of the interaction between different actors. The explicit definition of the content shows that different actors had a different perception on the projects content: documents such as the general arrangement of the vessel, design philosophy documentation or system boundaries. This different perception has considerable impact on the design process; it appeared that the design process not only functioned as a guiding design strategy, but also aligned perceptions of the actors.

Chapter 8, observation 2. Not all companies are willing to develop innovative solutions: The strategy tested in chapter 7 assumes\ willingness of the actors to develop innovative solutions. Within the experiments, it became clear that not all companies or actors are interested or capable in developing innovations. Reasons differed, in some cases innovations are avoided to mitigate risk (5, observation 1), in other cases personal, cultural or business experiences played a role.

Chapter 8, observation 3. Accepting a design strategy developing innovative solutions: In the experiments it appeared that the clients were aware of the approach, including the delivery of the GA late in the project and the development of innovative solutions. In the reference case, the design strategy was not explicitly defined in advance, causing considerable challenges throughout the project. During the interviews, the client's project manager mentioned that the lack of mutual understanding about how the project was developed caused frustration.

Chapter 8, observation 4. How companies work, the challenges of changing the design process: The design strategy asked of the involved actors to think about and describes their way of working. This is a challenging question; different actors questioned the theoretical framework or were reluctant to follow the steps. This also includes the 'not invented here' attitude, that means that different actors are reluctant to follow external guidance to support their development.

Chapter 8, observation 5. System developments matter: The design strategy was developed with a focus on the technical dimension of the interaction between the ship designers and system designers. During this process many of the involved technology partners were inclined to provide support, as they were able to influence the overall design. Although this is often the case (also in conventional ship design) the fact that the (technical dimension of the) interaction was made explicit amplified this for the involved technology partners.

9.1.1 Developing a new doubtful situation

The observations from both chapter 5 and 9 provide some insight in the challenges in the development of large complex vessels related to the social dimension of the interaction. These observations provide the basis for a new doubtful situation: how can we describe the social dimension of coevolving solutions to increase knowledge and expertise about these developments? The new doubtful situation, similar to chapter 1, is explored acquiring information from both practice and theory. This section takes observations from practice and exploring them with an initial set of theory to identify were further research is required and which potential research subjects can be defined.

9.2 The social dimension

Exploring the social dimension in ship design could yield interesting results, however, before an initial model for the social dimension is explored (9.2.3) the social dimension is initially pinpointed (9.2.1) and defined in more detail (9.2.2).

9.2.1 Identifying the social dimension

The term 'social' is regarded a fuzzy concept without a clear agreement on its meaning. The terminology often refers to society or its organisation, groups or companionships. The term is derived from the Latin 'socialis' or 'socius' meaning ally or friend (Oxford University Press, 2015). The social dimension of coevolving solutions concentrates on how two actors interact to achieve a common goal. The common goal in the early phases of these projects is solving a technical problem, the social dimension should include what the (personal or disciplinary) objectives of the individual actors and different perceptions influence the cooperation (figure 9-3).

The interaction discussed in this section is the interaction between actors. Such interaction aims to develop a shared agreement, a shared meaning, theorizing how meaning diverges and converges and finally how consensus is reached.

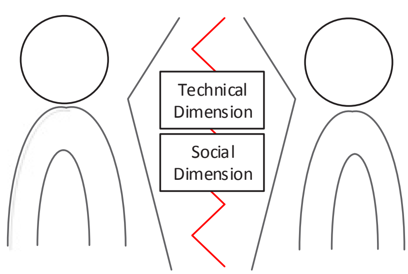


Figure 9-3. The two dimensions of the interaction in co-evolving solutions

9.2.2 Conceptualizing the social dimension

The observations discussed in section 9.1 illustrate the importance of the social dimension in developing innovative ship designs. Within the ship design industry (and many other technology dominated industries) this social dimension of innovating has not been explored in depth. To initiate research into this subject the literature on organisational sciences is briefly explored to provide a first conceptualization of the social dimension. The initial conceptualization is based on the transfer of knowledge and information, which is described as Syntactic, Semantic and Pragmatic (Jantsch, 1980; Carlile, 2002):

1. A syntactic description assumes that information is stable and consistent, with a shared perception among the different actors. In this situation, the focus is on the processing of information (Shannon & Weaver, 1949).
2. A semantic description assumes that, even if there is a common syntax (a common 'language') differences in perception occur: the objectives and sources of the differences related to interaction play a role in the analysis of the available syntax (e.g. Redding, 1972).
3. A pragmatic description assumes that there are consequences to the differences in perception, consequences that are dependent on the situation. In a pragmatic description, the interaction is used to modify the actor's knowledge structure to achieve a common goal. It assumes differentiation, dependence and novelty to be part of the communication (Bourdieu, 1977, based on (Peirce, 1877; James, 1907)).

The observations in section 9.1 illustrate that perceptions of the involved actors during the interaction play an important role (chapter 5 - observation 2, chapter 8 - observation 1). These perceptions have an impact on the development of innovative solutions, leading to either successful or unsuccessful developments: The pragmatic description of information and knowledge transfer therefore appears to provide the best basis for further research. The pragmatic description provides an initial framework to review the interaction, even though there is still no clear definition of which perspective should be evaluated. Drazin and his colleagues identify three perspectives (figure 9-4): The collective, intersubjective and the intrasubjective perspective (Drazin, et al., 1999). The intrasubjective perspective contains the internal cognitive processes; concentrating on the individual. The intersubjective perspective is shared between two or more individuals, developing a shared frame of reference and the collective perspective that represents the unfolding of change across multiple actors (ibid).

This chapter concentrates on the intersubjective perspective, developing a meaningful model which is used to improve the development of shared understanding and consensus (Smulders & Bakker, 2012). This chapter continues to refine the pragmatic description of the intersubjective perspective to explore the social dimension of ship design.

[1] The research methodology described in chapter 2 is also based on a pragmatic philosophical background, defined by the North American pragmatists such as James and Peirce (Peirce, 1877; James, 1907)

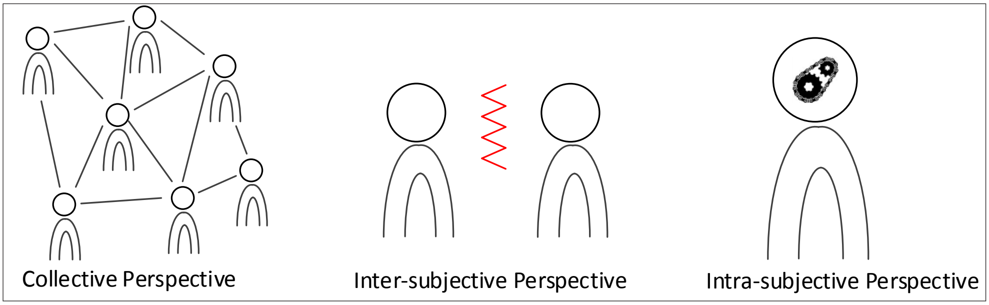


Figure 9-4. Different perspectives of socio-interactive interaction (based on (Drazin, et al., 1999)

9.2.3 Modelling the social dimension in coevolution and interaction

Selecting a pragmatic description of the intersubjective perspective provides an opportunity to select a theoretical framework which can be refined during further research. In this chapter, a model developed by Smulders and Bakker appears to be promising in describing the social dimension of designing innovative vessels (Smulders & Bakker, 2012). The model is visualized in figure 9-5.

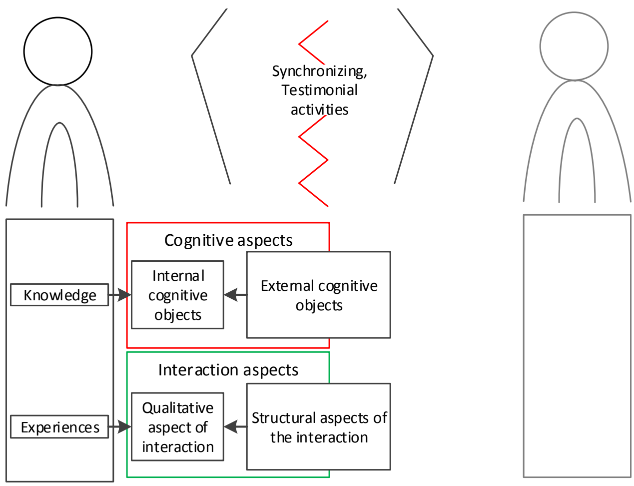


Figure 9-5. Modelling the social dimension between actors (based on (Smulders & Bakker, 2012))

The model in figure 9-5 is based on a set of social aspects (Smulders & Bakker, 2012) which included synchronizing and testimonial activities, cognitive aspects and interaction aspects. The cognitive aspects include internal and external cognitive aspects, similar to the interaction aspects; they include both structural aspects (external) and qualitative aspects (internal). The model in figure 9-5 represents only half of the modelled interaction: it is important to realize that even though the actors share external cognitive objects and structural aspects, the perception may be different (figure 9-6), the internal cognitive objects and the qualitative aspect of the interaction is different in both actors.

The model in figure 9-6 shows the three aspects shared among the two actors, influencing the boundary between them. Although these aspects are shared, they have a different effect, dependent on personal experiences and knowledge.

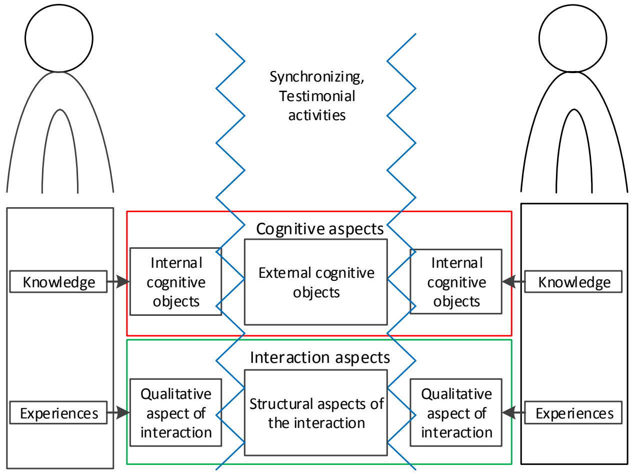


Figure 9-6. Disjuncture in the social dimension of interaction (based on (Smulders & Bakker, 2012))

The experiences of both actors influence their perception of innovation (chapter 5, observation 1), the willingness to innovate (chapter 8, observation 2), accepting a change in design strategy (chapter 8, observation 3). The knowledge of the actors has considerable influence on how objects are perceived (chapter 8, observation 1). The synchronization activities influence the alignment of social interaction and the available knowledge (chapter 5, observation 2), support changing the way people work (chapter 8, observation 4) and help to get new systems accepted (chapter 8, observation 5).

9.3 Exploring available practice with existing theory

The previous section identifies a possible description of the intersubjective perspective of social interaction. The theory identifies three shared aspects: synchronizing and testimonial activities (9.3.1), the external cognitive aspects (9.3.2) and the structural aspects of interaction (9.3.3). Each of these aspects is described and illustrated with examples from practice, complemented by a discussion related to their effect on the involved actors.

9.3.1 Synchronizing and testimonial activities

Smulders & Bakker identify the synchronizing and testimonial activities to incorporate all activities linking the cognitive aspects and the structural aspects of the interaction. Such activities include storytelling, totem building, thinking along, perspective taking & making, dialogue mapping and team reflection (Smulders & Bakker, 2012). The shared activities between actors aim to transfer ideas or synchronize understanding, influencing both cognitive and structural aspects of the interaction.

Within the experiments, two specific meetings had the purpose of synchronizing the involved actors: The first type of meetings were the kick-off meetings of each project. During these kick-off meetings the different actors were introduced and the approach for internal and external communication was set. In the case of the Van Oord Bravenes, this meeting was used to develop and align system boundaries and discuss the initial development for the systems. During these meetings the acceptance of the design strategy was founded (chapter 8, observation 4).

The second set of meetings were the workshops organized to synchronize perceptions on the design strategy. In the first experiment, USoS introduced the new design strategy as the Ulstein Design Process (UDP) to improve control during the design of the Ulstein AXDS. The documentation was challenging for several technology partners, who were reluctant to support such an approach. Two workshops were organized with two important technology partners, concentrating on the proposed design strategy and synchronizing the individual approaches, increasing the willingness to develop new solutions (chapter 8, observation 2).

The activities proposed in this section are used to align different actors during the design process, influencing both the cognitive and interaction aspects to improve cooperation and work towards a common goal.

9.3.2 External cognitive aspects

Different tools are used to improve the cognitive aspects shared among different actors during product development. Such tools include, amongst others: boundary objects, drawings, models, prototypes, mock-ups and stories. These tools are used to align internal cognitive aspects between different actors, improving interaction (Smulders & Bakker, 2012).

Within the design process of large offshore vessels the General Arrangement (GA) plays an important role as an external, cognitive tool. The GA, although each actor may read it differently, provides all actors with a framework for the development; a boundary object (Star & Griesemer, 1989). A boundary object is typically used to facilitate synchronization between different actors. In both experiments the GA as a boundary object was replaced in favour of the design strategy. This provided a hierarchical structure of working, instead of using the GA as a frame of reference. This change caused considerable unease for the different technology partners, as they had increased design freedom without the constraints of a predefined reference frame.

Tools such as the GA are used during the synchronisation or testimonial process to develop shared frames of reference, for example for the development of systems, but also to provide directions and develop a rudimentary mental presentation. In essence, these tools are used to align the resulting designs by different actors. However, in the experiments, the GA was not available in advance, and the role of the boundary object was taken over by the design strategy documentation, this influenced the way different actors saw the different documents (chapter 8, observation 1).

9.3.3 Structural aspects of the interaction

Smulders & Bakker identify hierarchical structures that can be applied to improve qualitative aspects of the interaction. These structures, the sequentially or reciprocal dependencies influence the experience of different actors during the project, improve the quality of the interaction as perceived by the actors (Smulders & Bakker, 2012).

The structural aspects of the interaction and their influence on the perception of the involved actors is one of the more complex aspects of ship design. The experiments made this structure explicit which challenged the involved actors. Several of them felt comfortable with the approach and mentioned the design philosophy as both necessary and inevitable, others were reluctant to follow this predefined structure as they would rather develop the project by applying a more conventional approach, with different acceptance of a design strategy (chapter 8, observation 3).

In both cases, the client's project team responded positively, seeing the changes as an opportunity to innovate design and process. However, several synchronization activities were required to align the technology partners that did not have a positive response. The structural (or the 'external') dimension of the interaction has considerable impact on the qualitative aspects such as standing, trust, nonverbal capacity and favouritism based on the actors experiences (Smulders & Bakker, 2012). However, the definition currently appears to be too narrow. During the experiments, the approach to communication, the way follow-up was conducted and design maturity were also mentioned as an influence on how actors saw the qualitative aspects of the interaction (chapter 8, observation 4). These elements do not have a place in the conceptual framework as proposed by Smulders and Bakker, and perhaps could be used to further improve the framework.

9.4 Researching the social dimension

The previous sections initiate an exploration of the social dimension of developing complex objects. The applied theoretical framework appears to provide an interesting basis. However, to conduct further research different approaches are required. This section illustrates three research subjects that could be applied to explore the social dimension in ship design: boundary objects (9.4.1), process models (9.4.2) and linguistics in synchronising activities (9.4.3).

9.4.1 Boundary objects

Boundary objects play a facilitating role in synchronizing towards shared frames of reference (Smulders & Bakker, 2012), concentrating on the development and effects of external cognitive aspects. Star and Griesemer identify boundary objects as stable representations of the current knowledge: representations that are shared among different problem areas and different actors (Star & Griesemer, 1989). The boundary objects are used as temporary anchors or bridges to a shared understanding. There are four types of boundary objects: repositories, the ideal type, coincident boundaries and standardized forms and methods. Each of these types play a role when cooperation between different actors is required but no consensus is available (Star, 2010). Boundary objects are used in new product development (NPD) to evaluate the role of knowledge in new product development (Carlile, 2002). Still, it is not used in a broader perspective to determine the effect on the internal cognitive aspects during product development.

The observations discussed in section 9.1 identify the General Arrangement (GA) as a key boundary object during the ship design process. This drawing (often made in 2D-CAD) is used by different actors for different purposes throughout the project, for example the development of systems, applied as a reference plan or as the basis for structural and production drawings. Interestingly, the GA changes role during the process. In the early stages, the GA is a sketch continuously modified and growing in respect to detail, in later stages the GA is a reference plan providing boundaries for the development of systems. In the final stages of the development, the GA is a description of the final solution.

Researching boundary objects can provide insight in which objects have considerable influence on the product development, what this influence is and how this influence may be applied in practice to improve control on the social dimension of the interaction during the development of innovative designs; an interesting prospect.

9.4.2 Process models

Process models are representations of the structure of the interaction: the design approach and the related documentation provided to the different actors during the experiments is one example of a process model. These models describe a structured approach to the interaction between different actors, without prescribing solutions. Within this dissertation, a process model was based on coevolution and interaction, modelled on the cohesion in system of systems (chapter 6). Although this is one example, process models can also include other representations of the hierarchical, sequential, independent or reciprocally dependent structure of the interaction such as stage-gate models applied in project management or the structure in parallel developments in concurrent engineering.

Such models can have considerable effect on the involved actors: in this research the differences in perception (chapter 8, observation 1), willingness to develop innovative solutions (chapter 8, observation 2) and the client's preference for such a process, instead of a design from the Ulstein portfolio (chapter 8, observation 3). This became particular evident after implementing a process model. Exploring the social effects of changing the approach during the development of innovative ship designs could provide insight in the qualitative aspect of the interaction. This research provided a first step in changing an approach within the ship design industry, still this dissertation did not explore the consequences to the qualitative aspect of the interaction as I lacked the required knowledge to evaluate these subjects. Subsequent research may benefit from theories drawn from the social sciences and research fields such as change management and business process reengineering.

9.4.3 Defining meaning; linguistics in synchronising activities

Exploring the social dimension in ship design requires research beyond the tools usually available to ship designers and other engineers. This section introduces a research tool that concentrates on linguistics and communication research to illustrate the potential of a broader research approach. Such an approach would be vastly different than the natural sciences based nature of this PhD, and is more akin to humanity studies.

The majority of this research explores the interaction caused by coevolving solutions, first in the technical dimension, complemented in this chapter by the social dimension of these interactions. The conceptual framework provided in section 9.2, based on the work of Smulders and Bakker (Smulders & Bakker, 2012) provides some insight in this social dimension. Many of the observations are directly based on verbal communication:

storytelling, thinking along and other synchronizing activities rely heavily on the impact and consequences of speech. The consequences and impact of wording, presentation and linguistic skills may be an interesting field to explore within the development of large, complex vessels, as they impact on the qualitative aspects of the interaction.

This potentially opens a broad spectrum of theories and frameworks that may improve the social aspect of interaction. These theories and frameworks for example include the work of John Austin and John Searle defining language as a tool to achieve a goal, the speech-act theory (Searle, 1969; Austin, 1975). Another approach may include the work of Habermas, who identifies that only when an actor develops a reasoning, another party is able to respond, playing an important role in defining which subjects are discussed while synchronizing (Habermas, 1984).

This is just a minor selection of potential tools and theories within humanity studies that may improve the review of the social dimension of the interaction. At this stage, a more complete review is impossible because of the technical background of this research and its author, but this initial sketch is sufficient to identify the potential of such an approach and to formulate the new doubtful situation.

9.5 Researching the social dimension in ship design

The initial section of this chapter provides some of the challenges seen in practice, challenges that could not be modelled and improved by the original model but require a different approach. Subsequent sections discuss potential models and tools that may improve insight in the social dimension of developing innovative solutions, which is an interesting field of research that has not been explored within ship design.These approaches could provide young ship designers and engineers from other professions with a theoretical framework to support personal observations related to the social dimension of developing innovative solutions. Furthermore, developing a scientific basis about the interrelation between technological developments and the social consequences within the teams developing these products could provide insight in the management and organisation of such projects. Both potentially leading to a more controlled approach in ship design.

Exploring the social dimension within the ship design practice will not be easy. First of all, the potential perspectives on innovative ship design proposed in the previous section require a different knowledge base compared to the knowledge available in the ship design industry: such perspectives stem from the social sciences and the humanities, whereas research in the ship design industry is generally based on the natural and formal sciences. The involved researchers are expected to have knowledge from both the social sciences (to develop the research) and the industry specific knowledge (to understand the technical dimension of the interaction). This combination of these two is difficult to acquire: part is taught at the university, but the remainder is learned from practice: as shown earlier, the industry is heavily dependent on the tacit or practice based knowledge. Researching this subject requires considerable input, which cannot be learned but is developed through experience. Smulders & Bakker mention that such research may be performed by multidisciplinary teams of researchers, instead of a single

PhD-research(er) representing only one discipline.Finally, the ship design industry is focused on technology and natural sciences. For such a subject it may be difficult to develop a research proposal containing sufficient technical content in combination with the proposals developed in this chapter that comply with both the challenges from the industry and meet the requirements of researching the social dimension.

9.6 Redefining the doubtful situation

This dissertation aims to improve control during the development of large, innovative ships. The conclusions in chapter 8 identify that managing the technical dimension of the interaction provides a successful first step, but that the social dimension of the interaction does play an important role in improving control during these projects.

Exploring the approaches and tools discussed in this chapter could lead to new insights in managing the social dimension and improving scientific knowledge about these processes. Such theory can be used to prepare ship designers for their work in practice. Based on this research, tools may be developed that support current ship design practice based on a newly developed scientific knowledge that not only supports the technical but also the social dimension of coevolving solutions. At present, the lack of a generally accepted theoretical framework requires such tools to be developed on a case-by-case basis, instead of a more generic tool capable of supporting the social processes during innovative ship design. This section draws conclusions (9.6.2) and defines potential research subjects (9.6.1) based on the previous sections.

9.6.1 Potential research subjects

This chapter aims to identify the social dimension, provide a first draft for a theoretical framework and introduce several research subjects that may improve the knowledge base related to the social dimension. Based on these observations, the following research subjects may be interesting for subsequent research:

1. The effect of boundary objects: Boundary objects play an important role during the synchronization of different actors. The documents have technological content, but the knowledge of the actors has a major influence on how they perceive these documents. In this project, the changes to the application of the general arrangement had considerable impact on the product development process, providing additional design space for the involved actors. The effects of boundary objects such as the general arrangement, the basis of design and requirement documentation on the social dimension is interesting to explore.
2. Influencing the qualitative aspects of the interaction: Section 9.3.3 discusses the influence of structural aspects on the qualitative aspects of the interaction. The introduction of the design strategy in the project described in chapter 7 influenced the structural aspects of the project, resulting in considerable impact in the perception and feel of the different actors involved. Still, other aspects may influence these qualitative aspects, such as project management skills, favouritism, verbal and nonverbal abilities. A more detailed research related to the aspects influencing the interaction aspects may improve the theoretical framework initiated in section 9.2.
3. Improving synchronization: The two research subjects discussed in the previous sections concentrate on the individual aspects in the model. The subsequent phase

can focus on the integration of both the cognitive and interaction aspects in a social process, aiming to improve the design process. Both aspects are combined in synchronization processes, which have distinct cognitive and interaction aspects. In the experiments two of these synchronization moments were recognized (subsection 9.3.1), both with a different purpose. The kick-off meeting as seen during the experiments aimed to synchronize project related aspects, while the workshop concentrated on aligning the structural aspects of the interaction.

9.6.2 Conclusions

This chapter identifies, illustrates and explores the social dimension of coevolving solutions and the resulting interaction to create a new doubtful situation for a next Deweyan inquiry. The conclusions from both chapter 5 and 8 identify the role of the social dimension in the development of complex objects, although the theory to describe this effect is not available in ship design literature. This chapter provides an initial exploration of theory and practice, to create a starting point for further research. Different research proposals are developed based on boundary objects, the qualitative aspects of the interaction and improving synchronization. The developments discussed in this dissertation could be used in subsequent research; however, these proposals concentrate on how the information is transferred and not on the content of the interaction.

Chapter 10

Conclusions and Recommendations

Based on the content of this dissertation conclusions (10.1) and recommendations (10.2) are drawn. This concludes the Deweyan inquiry, summarizing the developed theory and defining the new doubtful situation, challenges which require additional research.

10.1 Conclusions

This research explores how naval architects develop large, complex and innovative ship designs in practice. This broad research question is explored using a research strategy based on the Deweyan inquiry, which concludes with a warranted assertion (chapter 8) and a new doubtful situation (chapter 9). The main conclusions from this research are bundled here, which discuss introducing a new perspective on the ship design process (10.1.1), determining the technical dimension in the interaction based on cohesion in a system of systems (10.1.2) and the design strategy based on these observations (10.1.3). Further conclusions discuss the research strategy (10.1.4) and the effect of this research on practice (10.1.5).

10.1.1 Introducing a new perspective on describing ship design

The initial research question of this thesis was 'how are innovative, large and complex vessels developed in practice?". To explore the approach naval architects use both theory and practice were studied. A combination of theories such as CK theory (1.4.1) and systems thinking (3.5) provided the tools to show that ship designers allow creative solutions to develop on multiple levels of decomposition. These solutions on different levels of decomposition coevolved, resulting in considerable interaction between the involved actors (5.1).

The initial observations provided insight in the approach used to develop ship designs, but the available theory did not describe how interactions occurred beyond original system boundaries. In the case studies where coevolution was observed, the interaction was managed using short communication lines, allowing innovative items to emerge without a clearly defined design process (5.3.1). Which information was exactly part of this communication was not defined. As a solution a shift is proposed to describe innovative ship design based on coevolution and interaction among system levels, instead of concentrating on developing the ship design, system design and component design independently and sequentially (5.1.3).

To evaluate the shift in perspective a design strategy is developed based on coevolving solutions on two levels of decomposition. The technical dimension (the content) of the interaction beyond existing system boundaries is modelled and applied in this strategy (6.5). The approach was tested in two projects in practice, where it appeared to support the designers with a more control during the design process while still leading to innovative ship designs. Both projects were successful: the designs were innovative, clients were satisfied and positive feedback was received from the involved actors (7).

It appears that the new perspective proposed in this research based on the coevolution of multiple levels of decomposition and interaction provides a better description of the process followed in ship design. This shift in perspective provides better opportunities to describe the work of innovative ship designers, although there is still considerable work to be done in describing and validating the technical dimension of the interaction and exploring the social dimension of the interaction, as will be discussed in more detail in section 10.2

10.1.2 Determining the cohesion in a system of systems

To determine the design strategy the 'content' (or the technical dimension) of the interaction needed to be identified. Within ship design there was no theory available to describe the content of the interaction, therefore a model was developed determining the cohesion in a system of systems. The cohesion is determined using a system thinking based approach. Each individual system, subsystem or component is described by form, characteristics, performance and function (6.2). These elements have relations within and beyond their own system boundaries determining the cohesion within a system of systems, shown in figure 10-2.

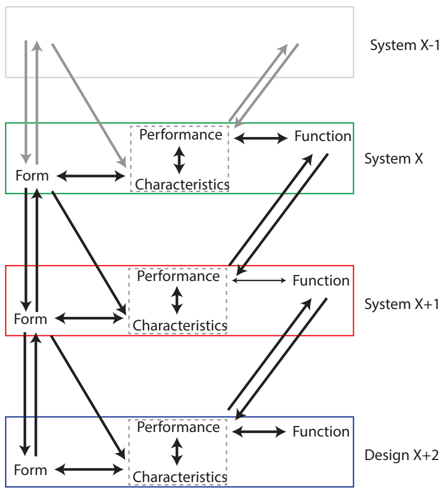


Figure 10-1. Modelling the cohesion in a system of systems (similar to figure 6-15)

The relations are based on a combination of observations in practice and available theory, discussed in more detail in chapter 6. The model of cohesion is used as a template for a design strategy specifically developed for coevolution of ship design and system design; the only strategy evaluated within this dissertation. However, the model is sufficiently generic to apply during the development of design strategies for other projects, other industries and other starting points, only when possible to develop the object to multiple levels of decomposition (8.5.1). If the model is effective in other industries and other starting points should be evaluated in further research (10.2.1). This design strategy was a success in both the eventual design and the process, but as the design strategy was based on a limited set of interactions it is not possible to draw final conclusions related to the model of cohesion. Still, further research is required to validate this model and the relations beyond the system boundaries.

10.1.3 An interaction-driven design strategy

To determine if the proposed perspective on ship design (10.1.1) and the model of cohesion in a system of systems (10.1.2) improved the description of practice a design strategy was developed based on the model of cohesion, allowing for coevolving ship design and system design.

The approach not only included the creative invention (development of new solutions) identified by McKesson (McKesson, 2013), in both the development of system solutions and new integrations (8.4.1), but also discussed the approach leading to the developments and the evaluation of the new design. This interaction driven design strategy (shown in figure 10-3) is applied in two projects in chapter 7 to test if the approach increased control during the development of innovative designs.

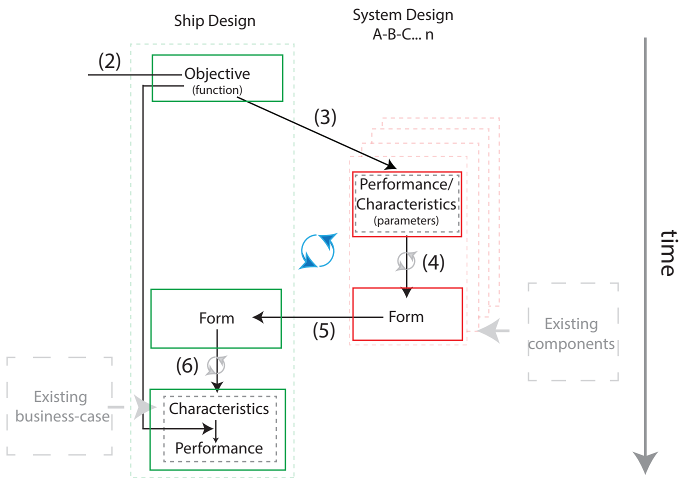


Figure 10-2. The proposed designs strategy (similar to figure 6-33)

The projects concentrated on system developments first, before developing the general arrangement. This is a departure from the approach usually taken in the ship design industry; where an existing design is modified to suit the requirements of the client. The design strategy provided structure to the initial phases of the product development. This resulted in different responses from the involved partners: some technology partners were happy with the opportunity to develop new concepts, others were more reluctant as they were more comfortable with modifying an existing design.

In both projects, the clients (represented by the project managers) were positive about implementing a new design strategy, which was different to the approach common in offshore ship design. Both projects resulted in designs considered innovative in comparison to other available vessels. The designs did not contain major showstoppers; both vessels were successfully developed further in subsequent projects. Although both projects were successful, several comments were made in the interviews after the conclusion of the projects. Different actors mentioned that the approach should mature, both in documentation and in theory. Furthermore, the approach described the technical dimension of the interaction, but did not provide a framework to evaluate the social dimension of the interaction. Both comments are taken up by USoS, who is currently developing this further beyond the confines of this research. The effect of the social dimension was discussed in chapter 9 and section 10.2.3.

In general, the design strategy resulted in two successful projects and it appears that the approach has a positive effect on interaction between different actors, both in the technical and social dimension. This strategy concentrates on the development of the ship design and system design, based on a required ship design function, constraining application further (8.5.1). The explicit nature of the strategy provides insight in the ship design process, but to validate these design strategies and in particular the model of cohesion further, additional research is required. One proposal is to evaluate the consequences of specific design strategies over multiple projects to determine the quantitative effects on the project parameters: time frame, resources and amount of rework, as will be discussed further in 10.2.1.

10.1.4 Explorative research in ship design

The research was initiated by a broad but challenging question: how are large, innovative ships developed in practice? Instead of the rationalistic research common in the maritime industry a Deweyan inquiry was applied to explore this question, aimed on discovery instead of validation and verification.

The Deweyan inquiry has two inherent methodological issues: the researcher's bias because of the engagement with the research subject and the effect of the researcher on the research subject. To increase scientific rigor and reduce during the observations in practice the rationalistic case study approach is applied, complemented by the sequential nature of the deweyan inquiry: each step strengthens and redirects the development of the theory throughout the research (2.3.2). The engagement bias is also taken into account in developing the individual interviews. The resulting quotes from the interviews were reviewed by the respected interviewees, to limit the influence of the researcher on the data. To develop theory further subsequent research would benefit from applying a rationalistic research approach, for example to validate and verify the model and methodology developed in this research.

Reflexivity was inevitable during the research as the experiments were based on the work of the researcher/practitioner. During these projects the researcher had both planned (intervention) and unplanned (reflexivity) influence on the research subject. Each project was therefore documented the influence of the researcher to allow for intervention to happen, but also to document, review and reduce the effects of reflexivity. Each experiment was influenced in a different amount to evaluate the effects of reflexivity. During the first intervention (the development of the Ulstein AXDS) I was involved as both practitioner and researcher. During the second project only the (initial) documentation was provided, providing more separation between the subject and researcher. In retrospect, one source of reflexivity is not mentioned. Throughout the research I was working at USoS, where we had considerable discussions on the development of large offshore vessels. The naval architects involved in these talks included those involved in the experiments; an effect which could not be avoided.

In this particular case, the Deweyan Inquiry was well-suited to explore the challenging question defined early in the project. The approach was able to handle the open nature of research, resulting in theory which is relevant, suitable and workable for this industry. Still, when starting a research within a technical industry based on the Deweyan inquiry, or any similar approach then following courses on qualitative research early in the project is advisable. Early access to knowledge about for example action research, grounded theory and case studies can have a considerable impact on the initial phases of the research.

10.1.5 The consequences of this research in practice

The final conclusions do not concentrate on the direct results of this research, but on the indirect effect this research had on practice. The Deweyan Inquiry does not only aim to develop new theory, but also intends to improve the current practice. In this particular case, the research aimed to improve control in the design of large, complex and innovative ship designs in practice. The observations discussed in this section are of the researcher, and do not reflect the USoS business strategy.

The research subject of this dissertation lies close to the core business of USoS; the conceptual and basic design of large, innovative vessels for the offshore industry. Throughout this research different naval architects at USoS became more and more interested in the theoretical background of developing such vessels. This resulted in increased awareness of the consequences of (often undocumented) decisions in the early design stages, in particular when an existing design was modified to suit the client's requirements. During the later stages of this research, (project) managers started to see the design strategy as a valid alternative to the modification of an existing design and in some cases better suited to the client's requirements and preferences.

The interaction-driven design strategy applied in the two experiments is developed further within USoS as the Ulstein Design Process (UDP) and is applied to several projects, ranging from small concept studies to larger development projects. Interestingly, this provides sales managers with the option to offer different design strategies, instead of directly proposing a portfolio design. The results from this research and the further applications of the theory (including the development of the related documentation) show positive response of the ship design industry, not only to the practical application but also on the theoretical background.

10.2 Recommendations

This research does not provide a final or conclusive method for the development of innovative ship designs. The explorative nature of the research provides insight, but also identifies starting points for further research. These recommendations listed below discuss the further development of the technical dimension of the interaction (10.2.1), discuss further developments towards actual control in innovative developments (10.2.2) developing other design strategies (10.2.3) and proposes research on the social dimension of the interaction (10.2.4). Finally, the recommendations propose a shift from teaching ship design based on projects towards teaching design fundamentals (10.2.5), which potentially improve the connection between practice and theory.

10.2.1 Further development of the technical dimension in interaction

This research explores the technical dimension of the interaction when coevolving solutions on different levels of decomposition emerge. The interaction and coevolution driven design strategy was successfully tested in two experiments. Still, different topics could improve by conducting further research:

1. Tools and activities: The design strategy applied in the two projects requires different tools and technologies compared to a process concentrating on a single level of decomposition. Such tools may include software applications supporting complex interactions, documentation describing the design strategy or software used to track and evaluate system boundaries. Further research could develop new applications to support the process proposed in this research.
2. Beyond coevolving ship design and system design: The model is tested in a methodology discussing coevolving ship design and system design. However, as shown in subsection 6.3.2 the approach may be applicable in different levels of decomposition as well. At this stage, the question remains if the model is valid in other industries, in particular when they develop large, complex systems that can be decomposed in different levels of decomposition. Several industries that could be part of such research could include aircraft, factory or civil engineering industry, or even other branches which manage a complex set of technology partners and other actors during the development of complex products. The generic definition of the framework developed in chapter 6 should make it possible to explore these applications.
3. Different types of creativity during the design process: Creativity plays an important role in the design of innovative ship designs. During the development of the theory in chapter 6 and the tests in chapter 7 it became clear that throughout the process different creative activities occurred: evidently, the development of new systems (based on sets of performance requirements) and the integration of new systems into a ship design both required the definition of new 'concepts'. However, the development of new system boundaries and the development of additional evaluation tools (8.4.1) also included conceptual developments: both the system boundaries and new evaluation tools are new and creative developments. Each of these developments require a different type of creative activity: the development of a new system based on a set of performance is not the same as the exploration of evaluation tools for ship design or the definition of system boundaries. These

different types of creativities necessary may result in a very interesting research.

4. Defining system boundaries: The system boundary definition, discussed in 6.3.2, proved to play a substantial role. During both experiments the systems are defined by the involved ship designers. These arbitrary system boundaries are not always correct, or even perceived in a similar way by the involved actors. Network theory may potentially support the tracking and evaluation of system boundaries, as shown by Killaars (Killaars, 2014). Still, such developments are in their infancies.

The explorative nature of this research does not aim to deliver a conclusive method to prescribe the way coevolving solutions occur beyond the system boundaries and the following interaction. Both industry and theorists would benefit if the proposed framework is developed, evaluated and challenged with further research.

10.2.2 Towards controlled innovation in complex objects

This dissertation aimed to describe and improve the development of complex, innovative objects in practice. This research partly delivers on this promise: it develops and tests an initial framework based on ship design practice and theory working towards more control during the design process. Still, further research is required, for example applying the model of cohesion and potential design strategies in different industries and different projects; validating and verifying the model. If developed further the fledgling framework can be used to create a better understanding of innovative design, actually taking control during such projects by measuring characteristics, detecting deviations and taking corrective action when necessary. This research only identifies several of the characteristics part of innovative design, a list which needs to be expanded before we can start discussing control.

10.2.3 Complementing research in design

This research concentrates on the design of large, complex vessels and does not aim to complement fundamental design theory. Still, the observations in this research appear to complement the applied CK theory with the idea of multiple levels of decomposition: at this stage, CK theory does not describe the creative development at multiple levels of decomposition (3.1.2). In particular: the theory does not appear to identify the idea of 'conceptual integration', where a new and conceptual system (in this research: ship design) is developed from a conceptual set of subsystems (6.5, step 5).

The explorative nature of this research makes it possible to identify new components for application in such design theories, but the focus of this research on a specific industry makes it difficult to draw conclusions and complementing more generic design theories. Still, the observations in this research could spark an interest into expanding design theories such as CK-theory to include more complex systems-of-systems.

10.2.4 The social dimension of the interaction

Both chapter 5 and 8 draw the conclusion that this research explored only part of the interaction: the technical dimension. The social dimension appeared to play an important role in the coevolution of multiple levels of decomposition. Chapter 9 explores this further based on the observations from the previous chapters, in order to identify and structure the challenges at hand when exploring the social dimension. Exploring the social dimension in ship design is a complex subject. The main challenge is to combine research strategy and knowledge from the social sciences with the technical knowledge in ship design: a research content based on natural sciences. This dichotomy of both fields within a single research is very challenging.

Such research may take many directions (9.6.1): potential research subjects include the role of boundary objects in ship design, influencing the qualitative aspects of interaction and the improvement of synchronisation activities. Exploring boundary objects appears to be most beneficial, these objects explore the role of both the technical and social dimension in a single object: combining both shape and content of the object, discussing knowledge, objectives and perception. Examples of key boundary objects in this research include the general arrangement and the design philosophy documentation.

10.2.5 Teaching ship design

The final recommendation returns to my personal experience as a student at the Delft University of Technology. Throughout my own Bachelor and Master ship design education concentrated on design projects with teams of other students, often applying iterative approaches such as the design spiral. The design projects concentrated on balancing and optimization and were often judged based on retrospective reviews of the designed vessels.

The observations from practice illustrate that (young, academically trained) naval architects could benefit from a more focus on creative and innovative design approaches, instead of a focus on engineering tasks such as balancing and optimization. This would provide young naval architects with additional knowledge and an initial framework to support their work in an industry which becomes more and more dependent on creative ideas to maintain competitiveness. The observations in this research suggest a framework which includes system thinking in combination with theory describing and identifying conceptual developments. Such a framework should at least support the objectives defined in section 6.1: Defining potentially innovative items, the structured involvement of technology partners, the support of integration and coevolution in weak boundaries and the timing of creativity in the design process.

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Appendix

Quote 4-1.	*"You can generalize this statement. You can see that we are very innovative in the selected lift-systems, perhaps even in the hull-form, but especially in the lift-systems and the overall concept. On the component level it is more of a basic principle that we use off-the-shelf components: components that are already standard available, to minimize any extensive development."*	*je kan het veralgemeniseren, wat ik net zei. Je ziet dat wij innovatief zijn in de liftsystemen die we gekozen hebben, misschien een beetje in de scheepsvorm, maar met name in de lift systemen en het overal concept. en het concept van single lift, maar op component niveau is het ongeveer een basisprincipe, dat we uitgaan van off-the-shelf componenten. Componeten die eigenlijk al standaard leverbaar zijn, om te minimaliseren dat er nog uitgebreide ontwikkeling nodig is, ook omdat je daarmee, om een aantal redenen: Ten eerste omdat dat vertrouwen geeft aan klanten, oliemaatschappijen, dat we niet zeggen, we gaan een volledig experimentele cylinder erin zetten, van een maat die nog nooit gemaakt is*
Quote 5-1.	*"We had to make an organisation, but we weren't given any time to do that, it was a very difficult start of the project: I was serving both as a naval architect and the project manager; handling the organisation structure, planning etc."*	*So we have to kind of make-up an organisation. And we were actually nog given any possibility to have time to do that. It was very difficult start of the project. I was serving both as a naval architect and head of the project, and handling of building organization, doing the planning and everything*
Quote 5-2.	*"As far I can remember, it took some time before we actually got drawings from them [the topside designers], but we were continuously pushed by the client. They wanted to see something from us; the first GA, the first hull, was therefore developed without much input from the topside vendors."* *"We didn't understand how UDS was working in the beginning, and that was a little bit frustrating; and we thought about when we should take action."*	*as I remember it took some time before we actually got some drawings from them. And then we were pushed by Statoil all the time: they want to see something from us. So the, first GA or basis of the, of the hull was, was developed without that much input from them, from the topside.* *We didn't understand how you were working in the beginning, and that was for some a little bit frustrating, and you wondered okay: when shall we take action*
Quote 5-3.	*"We tried to say to both the client and the two topside vendors that we needed to finalize the hull-design, the placement of the moon pools and the sizing, to move forward with the operability analysis and an additional study."*	*We tried to say, say to both Statoil and the two topside vendors that were there: now we have to lock the size of the hull to, to move forward with the analysis we need to do, with the motions, and the Marintek studies, and everything, and the placement of the moon pools were very important for us to more or less settle, and the size.*
Quote 5-4.	*"I think the client's project manager used a strategy of pushing, intimidating and 'scaring' us to do what he wanted us to do: if he said we would jump, then we jumped, it was almost a panic at the beginning; we did what he said, but that was not necessarily the way to move forward early in the project."*	*He was, I think he was very used to pushing and intimidating and scaring us to do, if he says jump, then we jump, it was almost like we had panic in the beginning, because (not understandable), we did what he said, but that did not necessarily be in the best, best way to move forward, early in the project.*
Quote 5-5.	*"The client really wanted to have the drawings; they wanted a concept that had to be realistic; it had to be built within the timeframe that they set, so there couldn't be any crazy ideas that have not been tried before."*	*Because they, they wanted to have: where is the drawing, we need some, get some information from the topside, we need to have a concept up. So they, and they wanted the concept, it had to be, realistic. It had to be possible to realise it, to build it actually within the timeframe that they had set. So it couldn't really be crazy ideas but has not that has not have been tried before, or something like that*
Quote 5-6.	*"I believe that the double X-bow [X-bow & X-stern] would not have been developed if we were not challenging them"*	*well, the double X bow I believe that it would have not been developed by will starting if we were not challenging them*
Quote 5-7.	*"One of the biggest disappointments was to get the topside vendors to understand that they were working on a ship, that they could utilize that ship: they wanted to draw a rectangle and put their equipment on a single deck."*	*one of my biggest disappointment was topside vendors, was that, having them understand that they were working on a ship, and was having the ability to blend into the ship and utilize the ship. That was very difficult because they wanted to draw a rectangle put their equipment on one single deck, and just,*

Quote 5-8.	*"One of the first things we said to the client during the initial kick-off was that we didn't have a linear design process; it's very iterative, but it doesn't follow a line: It's a cloud of skilled people working closely together, and I think it ended up being correct."*	*ne of the first things we said to Statoil in the initial kick-off was that we don't have any linear design process. We don't, it is very iterative, but it doesn't follow the design spiral, it doesn't follow a line, it's a cloud of skilled people just working closely together. That's what we do. It ended up being correct.*
Quote 5-9.	*"That was a big lesson learned: If you do these kinds of processes, you need an organisation to handle it and that should be available upfront, or else you will be losing to much valuable time."*	*That was a very big lesson learnt, if we are going to do this, and we are doing these kinds of projects then we need to have a plan for an organisation to handle it, and that had to be upfront, or else we losing too much valuable time.*
Quote 5-10.	*"The time-frame and having to work with many topside vendors was a big obstacle. If we could have worked with 1 topside vender; working closely, like we did with Bourbon Orca, we could work together for a good solution."*	*And, so, a very restricted time frame was a big obstacle, having to work with so many topside vendors, if we could work on really focussing on 1 topside vendor, sit together, work closely, like when we for instance when we did the Bourbon Orca, and the development there, we had defined, and work together for a solution*
Quote 5-11.	*"I think that we would have less influence if we contracted one vendor, who subcontracted the others; we would have less influence on the solutions, on the outcome, and it might not be the optimum for the business-case."*	*I believe that you would have less influence if we contracted only the one vendor, who subcontracted to the others. Then we would have less influence on the solutions, and we could give less impact on the outcome, it might not be the optimum for the business case*
Quote 6-1.	*"Both in the early design phases as well as in the basic-design phases, the development went, as it went. Sometimes, things just "happened". We now try to develop this into 'check' moments, where we consider certain solutions. It was difficult to plan, because we were developing something what we didn't know yet where it was going to end up, and it was without deadlines."*	*Ja, maar ook in je voorontwerp, of euh, niet zozeer in je concept, maar meer in je basic design, dat je, met de tanker is het, is het niet helemaal waar, is het een beetje gegaan zoals het ging. Waarbij soms dingen 'gebeurden' waarbij, nu ziet dat we daar wat meer, dat we daar gewoon proberen hardere, ja, geen deadlines van te maken, maar wel een soort, check-momenten proberen in te bouwen, waarmee we zeggen: ok, dit is een stuk ontwikkeling, maar op dit moment moet er wel een moment duidelijkheid komen van ok, we maken een keuze, gaan we links of gaan we rechtsaf. er was ook niet op te plannen eigenlijk: want je ging iets aan, waarvan je niet wist waar je heen ging. uiteindelijk werd de planning gestuurd door externe factoren en we hadden ook niet, een deadline, van we gaan met de bouw beginnen,*
Quote 6-2.	*"I think that we should change the way we manage such a project, compared to this project, to take control for example on the planning."*	*ik wil misschien, wat we anders zouden willen doen, en ik denk dat we dat ook anders doen, hoe we zo'n project sturen. En dat proberen we nu, ten opzichte van, van, de tanker, denk ik dat we meer proberen te sturen, kwa planning*
Quote 6-3.	*"I would like to be involved in the design; than you can change or modify the design of for example the hull, because that was already finalized when the oil & gas company stepped in."*	*Nou dan denk ik echt in het ontwerp. Want je kan dan natuurlijk je kan dan nog in het ontwerp van de romp bijvoorbeeld misschien nog wat aanpassingen of wijzigingen doen en dat lag er nu in feite al.*
Quote 7-1.	*"Before the kick-off meeting our naval architect approached me, if Ties his work wouldn't be interesting for this project. I looked at it, embraced and presented it to the client."*	*voor die kick-off meeting kwam Christiaan naar me toen van joh, het werk wat Ties aan het doen is dat ziet er wel leuk uit, kunnen we daar niet wat mee. Dus dat, daar heb ik toen even naar gekeken en omarmd en voorgesteld aan Statoil kortgezegd.*
Quote 7-2.	*"I would have to say, I was wondering in the beginning; are we taking on a fast-track project with a large, extensive method, is this the correct project to start such an approach. But at the end I think that the approach was suitable, and that we developed a good result."*	*moet zeggen in het begin, denk ik ook van gaan we niet met een hele grote methode of een veelomvattende methode, een fast-track project aan, concept ontwerp aan. Daar heb ik me in het begin ook wel afgevraagd, van, is dit nou echt het goede project om deze methode op los te laten. En vooral ook omdat die voor ons nieuw was. Maar achteraf moet ik zeggen dat het wel goed van toepassing was en dat er een mooi resultaat ligt*
Quote 7-3.	*"We felt a little bit uncomfortable, we were wondering if it would be possible to come up with specific solutions, but the client said that they were comfortable that you would come with specific concepts, and that you had qualified, traditional engineers on board."*	*I think at least Statoil told us, when we felt a bit uncomfortable, if that it will be possible, to come to any specific solutions, Statoil said that, they were comfortable, that Ulstein would, USoS meant, to come to specific concepts and that you had qualified people on board traditional, qualified engineers*

Quote 7-4.	*"Usually, after the kick-off we have a couple of weeks or months related to defining the correct requirements. In this case, it was very clear from the start; how the project would go, the conceptual idea etc. making it possible to develop our own things."*	*Maar dat is denk ik algemeen. Ik denk niet alleen, dat dit keer, niet, zoals ik al zei. Meestal na kick-off, zit nog een x aantal weken, slash, maanden problematiek van nou wat willen ze eigenlijk. En dat is, in dit geval was dat het niet. Dus dat was van het begin af aan, meteen duidelijk wat de eisen waren. Of in iedere geval, hoe je het project in moest gaan, en conceptual idee, dn dat je zelf dingen kan denken, kan bedenken*
Quote 7-5.	*"I can tell you, that both in the topside contractors and our own project team, there was concern: "I haven't seen anything", "where are the drawings", "what is happening". But I believed this was the way to do it, and I think I encouraged the others to believe that as well."*	*can tell you, that there was some, both the topsides, and also inside our project, there was concern. But I haven't seen anything, on Ulstein, where is the drawings, what is happening. And then it was, I believed in the way to do it. And I think I encouraged the other ones also to believe that.*
Quote 7-6.	*"That the one who is drawing the vessel doesn't think he is working on a circular vessel, while the one who designs the mooring system, thinks he is working on a slender mono-hull; that is something you need to clarify in the beginning."*	*Dat degene die de schuur over de hele bende aan het tekenen is, dat ie niet denkt aan een cirkel vormig schip en degene die het mooring systeem aan het ontwerpen is, denkt aan een hele lange mono-hull, met de turret voorop. Dat is wel iets wat je van tevoren af moet kaderen.*
Quote 7-7.	*"Before you started delivering, I was already familiar with the other contractor's documents, their processes. From your company, I knew nothing, until I got the first documents, and then you sent over 100 documents in!"*	*before you, Ulstein, started delivering, we have got, from other contractors, a lot of documents, so, we, at least for me; I was very familiar with their documents, with their process. And for you, and for Ulstein, I almost knew nothing, until I got the first document, and then they send 100 documents in.*
Quote 7-8.	*"I think your company is very innovative, that is also the feedback that we got from our discipline leaders."*	*Yeah, I think, Ulstein is very innovative. I'm very impressed, that was also the feedback that we got from some of the discipline leaders within Statoil*
Quote 7-9.	*"That was the feedback that we got from our client: there was a lot of innovation in the design, we developed something different than when we would have started with an example vessel, and modified that."*	*dat was ook de feedback die we van Statoil hebben gekregen natuurlijk. Dat er een hoop innovatie zit in het ontwerp. Dat, dat er dus iets anders uitgekomen is, dan dat je zou beginnen met een standaard of met een voornbeeld schip en dat een beetje aan zou passen*
Quote 7-10.	*"I would say that your result would have been a very good starting point for the next phase."* *"I heard from your client that both your and one of your competitors solutions contained no showstoppers; I don't know if you received this feedback."*	*very much would say, that your result from USoS would have been a very good starting point for the next phase.* *from what I've heard from Statoil is that your solution and the Inocean solution, they were, you know, they were almost, there was no showstoppers here, Statoil informed, I don't know if you received feedback or whatever. But they told us that it's been it wasn't any showstoppers here of course there were some areas for improvement.*
Quote 7-11.	*"You presented reasonable solutions, not just purely out of the box solutions."*	*Reasonable solutions were presented, not just out of the box.*
Quote 7-12.	*"You had two options: it was open and you left it up to the client, I think they were unsure which concept you were behind. You were playing two cards at the same time!"*	*No, you had both options on the table and, it was open and then it was a little bit up tot Statoil there. I think they felted a little bit, which one we shall pick, with one of the concept are you behind. Or have a preference you know, because you know, you're playing almost two cards at the same time.*
Quote 7-13.	*"I think it was a very arbitrary subdivision [in system boundaries] that appeared correct when we started. Still, after 1.5 months we came to the conclusion that it wasn't the correct subdivision in ship's systems."*	*Denk ook een uiterst arbitraire onderverdeling die toen heel erg handig leek, en dat we anderhalve maand later tot de conclusie kwamen dat het dus niet de goede onderverdeling was in de scheepssystemen*
Quote 7-14.	*"We had the freedom to make things easier, we did not constrain ourselves, and that really worked: in our office, not with our technology partners."* *"I think it [the process] is not only very liberating, but also a necessity."*	*Hadden we zelf nog de vrijheid om de dingen echt handiger te maken, we waren zelf nog niet zo ingeperkt. Dus het heeft wel heel erg goed gewerkt. Maar intern, niet naar buiten.*

Quote 7-15.	*"I was expecting that they [the technology partners] would be challenged to show this knowledge and use it to develop and improve something."*	*Ik had verwacht dat zij het leuk zouden vinden en een uitdaging zouden vinden om die kennis tentoon te spreiden en te gebruiken om iets beters te maken.*
Quote 7-16.	*"I think I was a little bit naïve in that, because we like the way we work, we know what we do, and we are used to it."*	*ik denk dat ik daar een beetje naïef in ben geweest. Omdat de manier waarop wij werken is het vinden we vinden we heel prettig. En dat, we snappen wat we doen en de manier waarop wij werken, vinden wij, dat dat zijn we gewend.*
Quote 7-17.	*"I got to know the process, and got to know what you were doing, that made it better. I think it's a good process, but maybe it should be more matured."*	*I got to know this process, and get to know what you were doing, and then, it was getting better, afterwards. I think it's a good process, yeah, but maybe it should be more, let's say, matured*
Quote 7-18.	*"I think a little bit more effort could be put in to make it easier for you. You had a good presentation, it would be good to follow up on that presentation."*	*I think a little bit more effort could be put in, I think it would make it easier for you, if you had a good presentation and so on, but to follow up on that presentation*
Quote 7-19.	*"I expect that you get different results, if you use this design approach as a guide-line, and develop this 2 or 3 times, because you get more knowledge about the design freedom, and you start using that. If you use the approach for the 4th time, then you think: can we do something completely different, with the same functionality but an overall improvement? Perhaps!"*	*En als een guidline gebruiken en ik denk ook als je dit deze design-methology misschien 2 of 3 keer doet, dat er ook andere resultaten uitkomt omdat je weet wat je vrijheid is en dat je daar dan waarschijnlijk ook meer gebruik van gaat maken En misschien als je het de vierde keer doet dat je denkt van. Kan ik nou echt iets heel anders verzinnen wat ook op dezelfde functionaliteit uitkomt. En overall een verbetering is. Misschien wel.*
Quote 7-20.	*"One of the difficult aspects is that we didn't have a general arrangement, but we communicated that throughout the project. To the client, that's a risk; when you are working for 3-4 months, he hasn't seen a GA. To the client's feel, that is difficult to manage, to check."* *"The conventional approach is to get a General Arrangement, and they just fit their equipment in."*	*Door het hele proces heen. Maar dat is wel een, dat is voor de klant, de klant ziet dat als een risico. Want die is, die is al drie-vier maanden onderweg en die heeft nog niks gezien. Dus die kan het proces, kan die moeilijker, voor zijn gevoel kan hij dat moeilijker managen, en controleren.* *The conventional way is to get a General Arrangement during and then they fit their equipment into it.*
Quote 7-21.	*"I think it is good to say that the approach, with its focus on specific design aspects, is very suitable for the feasibility phase, and partly for the concept phase. During these phases you want to determine the potential of a design, and then you have to look at certain aspects."* *"One other advantage of this process is that you can develop the argumentation, more than we do when we develop a conventional design. I think choices were well supported with both advantages and disadvantages, especially compared to a normal concept or basic design."*	*Ik denk, het goed te zeggen is dat de methode van het focus op bepaalde ontwerp aspecten, die is heel goed geschikt voor feasibility fase, en gedeeltelijk voor het concept fase, daar is het leuk voor. Feasibility wil je haalbaarheid van een ontwerp vastleggen. En dan moet je naar de bepaalde dingen kijken of die haalbaar zijn.* *maar dat is wel een voordeel van dit systeem waarbij je dus die argumentatie kunt ontwikkelen, in het process, Wel meer als dat we in een normaal standaard ontwerp doen. Ik denk dat keuzes beter onderbouwd zijn met voor en nadelen en met argumentatie als dat in een gewoon basic design gebeurd, een concept design.*
Quote 7-22.	*"There was an existing system that the client uses, and that has been an important guideline for several design choices, well, we tried to maintain the facets that were working well."*	*er is al een bestaand systeem van vanOord, en dat is wel een belangrijke leidraad gebleken, achteraf toch wel, voor een aantal ontwerp keuzes, omdat, ja, we hebben toch geprobeerd de facetten die nu goed werken in de praktijk, en op de huidige schepen, om die te bewaren.*
Quote 7-23.	*"I think to describe what happened in this subdivision [the subdivision of the flexible fall-pipe system], that it's difficult to keep these problem areas separate; I noticed that, during the process, things continuously merge, because we were looking at the optimal cooperation between components, instead of optimizing different aspects."*	*, ik denk dat het misschien meer, beter uitleggen is, het is lastig geweest al die probleemgebieden apart te blijven beschouwen, ik heb wel gemerkt dat je op een gegeven moment toch tijdens het proces gauw dingen al samen komen, en dat je toch al kijkt naar meer samenhang en een optimale samenhang eigenlijk, dan, eerst op elk ding, apart deel optimaliseren.*

Quote 7-24.	*"There was a rough layout available how the vessel should look like: the main dimensions, the hold, were given. We engineered the vessel around this setup."*	*er was al een redelijk grove opzet gemaakt van dit moet het ongeveer gaan worden. De hoofdafmetingen waren bepaald, en er was een hold. Die hebben we van IDEA, van Marcel gekregen. Daar hebben we eigenlijk gewoon het schip omheen ge-engineerd, ontworpen.*
Quote 7-25.	*"Before we started, 6 weeks of research was already developed, based on that, they delivered a series of constraints. That means there was a very interesting meeting for the naval architects where these constraints were set. This meeting would give more feeling to the priorities of the constraints."*	*Voordat ze beginnen wordt, er is als het ware al 6 weken onderzoek gedaan. En daar zijn, een aantal randvoorwaarden op tafel gelegd, daar is een keer een meeting geweest waar al die, eigenlijk die, die, die randvoorwaarden bepaald zijn, en ik denk dat dat juist dat degene is, waar, prettig is van: waarom doen we dit, dan krijg je het gevoel erbij, dan krijg je veel meer het idee wat er echt gefixeerd is*
Quote 7-26.	*"Designing like this makes it, sometimes painfully, clear what kind of consequences the limitations have, and that was something they ran into at their internal client; they develop a wish list, but they don't see and understand the consequences."*	*op deze manier ontwerpen is, euh, het heeft heel snel voor hun pijnlijk duidelijk gemaakt wat, de grens voor gevolgen kan hebben en dat is eigenlijk hetgene waar we steeds tegenaan lopen is dat de interne klant van-vanOord, dat is de offshore afdeling, die stellen een wensenlijstje op en elke wens heeft een gevolg, en ze zien de gevolgen niet.*
Quote 7-27.	*"It is truly a break with the past, It looks fundamentally different, It's the first DP3 vessel; it's the first vessel that actually came from a clean sheet, no it is definitely an innovation."*	*een breuk met het verleden, qua smoel, hij ziet er toch echt fundamenteel anders uit als een bulk carrier, marktgebied, DP3; is ook voor ons het eerste DP3 schip ik bedoel, eerste, eerste boten die echt vanaf vanaf een blanco vel tot stand gekomen is. Nee, zeker innovatief.*
Quote 7-28.	*"I don't think that the vessel is revolutionary. In my opinion the vessel consists of known systems, structured differently; I know that people call this innovation, but I don't have the feeling that we made a large leap in the ship-design, like we did in the tower design [the flexible fall pipe-system]."*	*ik vind het ontwerp niet heel revolutionair. Dat komt een beetje omdat het bestaande systemen, op een andere manier gerangschikt zijn. En dat wordt wel innovatie genoemd, maar ik vond dat eigenlijk, maar ik heb het gevoel niet dat er een stap, dat in het scheepsgedeelte niet echt een stap is gezet. In die toren wel, dat is wel echt een stap verder dan wat we waren*
Quote 7-29.	*"The watertight subdivision, the fall-pipe installation, the system to connect the buckets and chains, the transport systems for the rock, these are all never used before on a fall-pipe rock installation vessel."*	*die waterdichte indeling, waar we ons al een paar keer over gehad hebben, die is innovatief, dat is in de valpijp wereld in ieder geval, nooit op deze manier gedaan. De stortinstallatie wordt innovatief, er komt een heel nieuw systeem op om bucket's en kettingen en alles daaraan, zonder dat daar mensen bij betrokken zijn. En het type, type transportsysteem, dat aan boord komt dat is ook heel innovatief. Nooit gebruikt om dit soort schepen.*
Quote 7-30.	*"I think that both the fall-pipe and the watertight subdivision were developed separately, ant that this worked very well; we had discussions with the classification society, we optimized them separately, but they combined beautifully."*	*Ik denk inderdaad dat, de valpijp, en bijvoorbeeld de waterdichte indeling van het schip, dat dat wel heel goed juist eerst apart bekeken is, er zijn toen ook al gesprekken geweest met bureau Veritas bijvoorbeeld, over die waterdichte indeling, dat is echt geoptimaliseerd los van elkaar. Dat is wel heel mooi later samen gekomen.*
Quote 7-31	*"I think that, if you look at the tower [the flexible fall pipe-system], that we actually defined too many systems, too many functions. If we missed something; should have selected a system that we didn't? No, not really."*	*ik denk dat, als je naar de toren kijkt, is het vooral geweest dat we misschien teveel systemen hebben geïdentificeerd daarin, teveel functies, of teveel deel. Of we iets gemist, als we achteraf terug kijken, dat had een systeem moeten selecteren, die we niet geselecteerd hebben? Nee, niet direct nee,*
Quote 7-32.	*"I think, from the day we started, that we focussed on the correct items; of course you need the shipbuilding aspects to get the bulk of the costs clarified, I know that, but I think I preferred to have started even a year earlier with the rock-dumping installation, but that was just not possible."*	*ik denk dat we vanaf dag één gefocust hebben op de juiste dingen. En, uiteraard heb je natuurlijk, dat scheepsbouwkundige deel nodig om het bulk, bulk van je prijs scherp te krijgen, dat weet ik, maar: ik had nog liever gezien, maar dat was gewoon in mogelijk, dat we bij wijze van spreken, jaar eerder alleen met die stort installatie begonnen waren. Maar ja, dat zat er gewoon niet in.*
Quote 7-33.	*"I think that the project approach was the correct one for this client, but in this specific vessel, that all systems were clear enough, and that such an approach would be unnecessary; therefore I think that the results of both methods would be similar."*	*wat ik denk, dat qua project aanpak is het wel een goeie aanpak geweest voor de klant, maar ik denk alleen dat het schip te duidelijk, dat er, dat alle systemen duidelijk genoeg waren, dat het niet nodig was. En daarom denk ik ook dat, het eind ontwerp van beide methodes hetzelfde zou zijn.*

Quote 7-34.	*"The client was very positive, we mentioned in the beginning that they wouldn't get a GA of the vessel until later in the project, but that was no problem what so ever."*	*Heel positief, ja, die vonden het, die waren heel positief over eigenlijk. Want ook wel, in het begin aangeduid van, let op: door dit proces heb je dus niet vanaf het begin al een GA van het schip, die komt pas later, dat was geen enkel probleem.*
Quote 7-35.	*"You generate that freedom when you modify a Deepwater-enabler with engine rooms that shift from front to aft, you have new holds, the accommodation is reduced from 240 to 60. Eventually you end up with a new vessel, and that generates that freedom."*	*die, die vrijheid die komt er vanzelf op het moment dat je zo'n deepwater enabler, even grof gezegd, als uitgangspunt neemt, en vervolgens komt je hele je hele-enginerooms gaan naar achteren en je hele middengedeelte met holds en feeders, dat past eigenlijk ook niet in het, dus daar moet je ook al. Dus dat hele stuk, plus accommodatie van 240 naar 60 man. Eigenlijk begin je sowieso al soort van opnieuw, dus de vrijheid ontstaat vanzelf op het moment dat je gewoon*
Quote 7-36.	*"It provides freedom that you don't need to bother with other systems; if you try to design a ship incorporating all systems, then it's very time-consuming because you are taking all potential parts and interactions into account. By focussing on one system, and solve the rest when we run into something, you can improve focus and speed."*	*het geeft in zoverre vrijheid dat je minder rekening hoeft te houden met andere dingen, en als je, het punt is als je in een keer een schip ontwerpt met alle systemen in gedachten, dan, ben je heel lang bezig om 1 systeem goed uit te denken, omdat je alle mogelijke systeempjes wil afhangen. En door te focussen op één systeem en dan, de rest lossen wel op als we er tegenaan lopen, dan ga je, dan hoef je geen zorgen te maken over de andere systemen, en gaat het sneller en gefocuster.*
Quote 8-1.	*"We tried to cover the entire ship with all the 'system area's'; I think that is something that we wouldn't do anymore, based on our experiences"*	*nog steeds geprobeerd om het hele schip wel te coveren, met al die interesse gebieden, ik denk dat dat nou typisch is, dat we achteraf niet meer zo zouden doen*
Quote 8-2.	*"I think it was a very arbitrary subdivision that appeared correct when we started. Still, after 1.5 months we came to the conclusion that it wasn't the correct subdivision in ship's systems."*	*Denk ook een uiterst arbitraire onderverdeling die toen heel erg handig leek, en dat we anderhalve maand later tot de conclusie kwamen dat het dus niet de goede onderverdeling was in de scheepssystemen*
Quote 8-3.	*"There should have been a process looking at topside solutions before starting with integrating the solution. If a topside vendor would have started the project 6 months before us, we could actually have a possibility of an integrated, reliable, overall solution."*	*So, there had, there should have been a process on looking at topsides solutions before starting to look at the integration process. How to integrate the solution. So you had a, if the topside vendor had started on the project half a year before us, and we had, some more time, then we actually could have, I think, have a possibility of have an overall integrated compact and reliable, better solution*
Quote 8-4.	*"I think, from the day we started, that we focussed on the correct items; of course you need the shipbuilding aspects to get the bulk of the costs clarified, I know that, but I think I preferred to have started even a year earlier with the rock-dumping installation, but that was just not possible."*	*ik denk dat we vanaf dag één gefocust hebben op de juiste dingen. En, uiteraard heb je natuurlijk, dat scheepsbouwkundige deel nodig om het bulk, bulk van je prijs scherp te krijgen, dat weet ik, maar: ik had nog liever gezien, maar dat was gewoon in mogelijk, dat we bij wijze van spreken, jaar eerder alleen met die stort installatie begonnen waren. Maar ja, dat zat er gewoon niet in.*
Quote 8-5.	*"You need to find a balance between a certain design-depth in a system and to take the time to bring it all together in a ship-design, to avoid surprises."*	*Tot op het lagere niveau en dat is, is ja het je zit ergens je moet een compromis vinden tussen een bepaalde diepgang in het systeem, en het op tijd bij elkaar brengen van het hele scheepsontwerp, om niet voor verrassingen te komen staan*
Quote 8-6.	*"My first impression was that I really liked it, I liked the approach but I thought it was going to be a struggle; everybody likes to work the way they have always done and it's a challenge to try to change people, to have them think differently. Your approach required that you inspired people."*	*My first impression was that I really liked it, I liked the approach but I thought it was going to be a struggle; everybody likes to work the way they have always doneand it's a challenge to try to change people, to have them think differently. Your approach required that you inspired people."*
Quote 8-7.	*"When we had the workshop: that clarified everything. It was the way we usually do this, but now we just document what we do."*	*when we had the workshop, and we got clarified everything, it was, this was, this is actually the way usually do it, but we just document what we do.*
Quote 8-8.	*"At first, they were not used to working like this, secondly, we were not used in working like this. The principle of this much-discussed design procedure, here as well, was that we start to think about what the design problem actually is and how we can solve it as efficiently as possible."*	*Om te beginnen waren ze helemaal niet gewend om zo te gaan werken. Ten tweede, wij waren het niet gewend om zo te gaan werken. Dus het principe van de veelbesproken ontwerpmethode, ook hier. Is dat we beginnen met onszelf af te vragen wat we nou eigenlijk het ontwerp probleem is wat we proberen op te lossen en vervolgens hoe je dat zo efficiënt mogelijk zou kunnen doen.*

Quote 8-9.	*"The way Ulstein handled the project very professional; you took to the task, was very good in the interfaces, and when you saw that an interface was an issue, a challenge for the project, then you took responsibility, regardless if it was inside your scope."*	*in regard with, the way, the project with the hull from Ulstein, was handled, I think it was very professional. You took responsibility, took the task, was very good on this interfaces, you see, you see that when an interface was an issue, and a challenge for the project, then you took the responsibility, regardless if it was inside, this, scope of work*
Quote 8-10.	*"I can only say that in the beginning of the project we were struggling in understanding how UDS developed the concept. It took some time before we saw the results from them, but after a while we understood that the way you dealt with the project and developed technicalsolutions was very good."*	*the only thing that I can say is that in the beginning we were struggling, in, in understanding Ulstein's methodology of concept development. It took a time before we saw the results of Ulstein, but after a while we understood that the way you dealt with the project was very good, the, the, the way you developed the technical solutions was quite good actually.*
Quote 8-11.	*"To be certain that we had the correct solutions of each sector, we then made a selection which combination of techniques was implemented. I think that's what happened, while I expected that the technology partners would make that choice!"*	*om er zeker van te zijn dat we daadwerkelijk de juiste oplossingen, zeg maar, uit die sectoren kennen en dan gaan we bij mekaar zitten en kiezen we welke combinatie en technieken dit wordt. Ik denk dat het zo uiteindelijk is gekomen. Terwijl ik eerder het gevoel had: we leggen die vragen allemaal bij de technology partners neer en zij zeggen je moet dit, je moet dat hebben*
Quote 8-12.	*"We were used to work on project, focussing on the solutions, not argumenting the solutions. We selected a solution, moved on, see if it works and then move further; now we had to argument everything."*	*because we usually were working on a project, and working, focusing on solutions, and, not argumenting to and for, against the solution. Chose a solution, move on, see if it works, and then state that this works, and then, move along, now suddenly you have to argument*
Quote 8-13.	*"That is our conventional of way of working; the creative process within USoS only occurs during the first three days, when an experienced ship-designer develops the General Arrangement. As the GA was not available, multiple people had the possibility to develop all kinds of potential solutions, we were creative for 4 months, not just 3 days."*	*Dat is onze normale manier van werken, houd eigenlijk in dat het creatieve proces wat binnen Sea of Solutions zich afspeelt, dat is eigenlijk alleen maar gedurende die eerste drie dagen dat een ervaren scheepsbouwer bezig is het algemeen plan op te zetten. Toen nu dat algemeen plan er niet was en er een aantal mensen in hun hoofd met allerlei deeloplossingen al half bezig waren hier op kantoor hebben we eigenlijk vier maanden de tijd gehad om het algemeen plan op te zetten, dus we zijn vier maanden creatief geweest in plaats van 3 dagen.*

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About the author

Ties van Bruinessen was born on the 31st of May 1985 in Aardenburg, the Netherlands. After an eventful first week he grew up in Aardenburg, attending primary school at 'Op Dreef'. He started grammar school in 1997 at the Zwin College, receiving his diploma in 2003.

Subsequently he started his study of Maritime Technology at the Delft University of Technology. After finishing the Bachelor of Science in august 2008 he continued with a Master of Science in Marine Technology, with a specialization in ship design. As part of his master he attended two semesters at the NTNU in Trondheim before finishing with a graduating work concentrating on automatically generating layouts for a US Coast Guard offshore patrol vessel.

During his studies he was part of the Froude bar committee, part of the board of the Student Sailing Association Broach and chairman of the Delft Challenge foundation. During this time he was competing in various world championships and the Tour de France á la Voile 2007 and 2010. In addition he worked part-time at Damen Shipyards Gorinchem in support of the Fast Ferries department.

After his MSc graduation in May and the Tour de France á la Voile in July 2010 he started to develop the initial ideas for a PhD research concentrating on the design of large, complex ships. The project started in January 2011 together with Ulstein Sea of Solutions and the Delft University of Technology (Section of Design Production and Operation). The work in the PhD was close to the core business of Ulstein and the results of the PhD are currently implemented as the Ulstein Design Process.

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Dat er andere eisen aan een promotieonderzoek gesteld worden dan aan enig ander project werd mij al snel duidelijk. In de afgelopen jaren liep het (schrijf)proces niet altijd even soepel, juist daarom wil ik Hans en Frido heel erg bedanken voor de tijd en energie die jullie in mijn ondersteuning hebben gestoken. Erop terugkijkend denk ik dat elk van onze discussies de kwaliteit van mijn werk heeft verbeterd.

My research is largely based on the discussions I had with a wide range of people at different companies and universities (including the Delft university) over the last couple of years. As they were both English speaking and Dutch this small section will be in English. During each discussion I was happy that everybody took their time to read my work, discuss experiences in specific projects, illustrating their perception of innovation or to discuss how they handle innovative developments. A large number of these discussions are part of my source material, but each and every one of them influenced me and this research on how we innovative in the ship design industry. Thank you for your time and effort.

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en toe terug ging naar zeeland, die mij, al dan niet nuchter, door de studie heen hebben gesleept. Die het met mij hebben aangedurfd in 1 huis te wonen of waar ik mijlenver samen mee op een boot hebben gezeten. Voor het af en toe afremmen, mij met beide voeten op de grond te houden en voor de vele, vele slechte grappen, koppen thee, etentjes, reizen, snickers / whinegums/ boterhammen met kaas, salami & curry, kerstdiners, biertjes, lestertjes, films en weekenden weg: De Schroef, EduP'tjes, Mummaduck, nieuwe & oude vrienden, Bedankt, en dat er nog vele slechte grappen mogen volgen.

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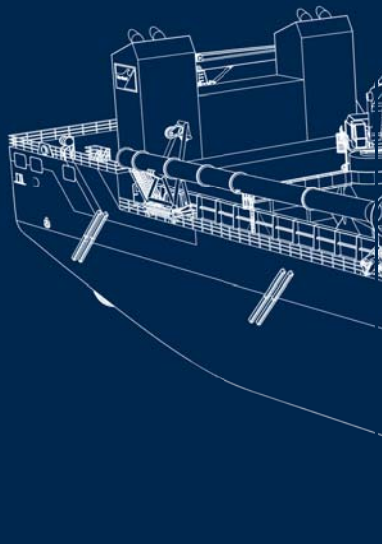
Lieve Emma, deze promotie heeft veel tijd en veel energie gekost maar in de afgelopen jaren heb je altijd naast mij gestaan, mij gesteund en vooral heel veel geluisterd: dat is mij alles waard. Het is fijn dat je naast mij staat en dat we samen vooruit kijken.



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