Synne Frydenberg

# CULTIVATING SERENDIPITY IN DESIGN COMPLEXITY

Exploring Designs of Augmented Reality Technologies for Ship Bridges

Arkitektur- og designhøgskolen i Oslo
The Oslo School of Architecture and Design

PhD thesis

Synne Frydenberg

# CULTIVATING SERENDIPITY IN DESIGN COMPLEXITY

Exploring Designs of Augmented Reality Technologies for Ship Bridges

ISSN 2703-691X
ISBN 978-82-547-0370-0

CON-TEXT
PhD Thesis 126

A DOCTORAL THESIS SUBMITTED TO
The Oslo School of Architecture and Design, Norway

PUBLISHER
Arkitektur- og Designhøgskolen i Oslo

COVER ILLUSTRATION
Field research expedition to the West Ice (Greenland) with KV Svalbard, Lasse Thomasgård

PRINTED BY:
Aksell

# CONTENTS

# PART II (PUBLICATION 1–6)

## ABSTRACT

Designing augmented reality (AR) systems for ship bridges poses intricate challenges for interaction designers due to the unique complexities involved in working with this novel interaction material in a dynamic and unpredictable environment. The absence of established design precedents and guidelines for AR systems exacerbates these challenges, thereby reflecting a broader need for guidance in navigating the rapidly evolving digital landscape of interaction design.

This thesis aims to explore and identify how design complexity can be effectively managed by introducing serendipity into the design process. Employing a research-by-design and research-into-design approach, this study utilises embedded case studies to contextualise design complexity within the specific context of designing AR technology for ship bridges. It develops conceptual frameworks, practical methods, tools, and approaches to illustrate how serendipity mechanisms and qualities can be cultivated and pragmatically integrated into the design process.

Further, this research highlights that designing AR systems for ship bridges entails grappling with various complexities, including interconnected systems, unfamiliar environments, and the challenge of assessing efficiency, user experience, and situational awareness in high-risk domains. Limited research and practice in interaction design further emphasise the need for adaptable frameworks and establishment of design precedents.

In this thesis, the navigation of design complexity is conceptualised through the deliberate cultivation of serendipity across different aspects of the design process. The case studies provide insights into an effective, pragmatic strategy that can be employed by interaction designers, stakeholders, and users in exploratory, practice-led design. This approach defines design complexity along two dimensions—design requirements and formgiving concerns—to support sensemaking and decision-making in a complex design landscape. Additionally, it conceptualises serendipity mechanisms, values, and qualities, thereby promoting attentiveness to serendipitous cues, recognition of patterns, seizing of opportunities, and creating of conducive conditions for serendipity.

The outcomes of the case studies include conceptual frameworks and design exemplars that contribute to the development of design precedents and practical support for interaction designers working in the maritime domain. In addition, this research—conducted through design—also informs research in design by exploring how design complexity in real-world cases are navigated and cultivated for serendipitous outcomes in various design processes.

As the discipline of interaction design grapples with the challenges posed by novel interaction materials, including issues like unfamiliarity, technical complexity, and novel formgiving qualities, alongside the evolving digital ecosystem, there is a pressing need to establish new strategies for managing design complexity and harnessing the potential of unexpected discoveries. This thesis contributes to the ongoing evolution of interaction design by providing conceptual frameworks, practical tools, and design exemplars that not only describe but also contextualise the cultivation of serendipity within the complexities of real-world design scenarios, thereby empowering interaction designers to navigate the uncharted territories of emerging interaction materials and the ever-expanding digital landscape.

**Keywords**: Design complexity, Augmented reality, Interaction design, Serendipity, Practice-driven research, Case studies.

# LIST OF PUBLICATIONS

## Appended Articles

### Publication 1

Frydenberg, S., Nordby, K., & Eikenes, J. O. H. (2018). Exploring designs of augmented reality systems for ship bridges in Arctic waters. In *Proceedings of the RINA international conference on human factors*. Royal Institution of Naval Architects.

### Publication 2

Frydenberg, S., Nordby, K., & Eikenes, J. O. H. (2019). Serendipity in the field. Facilitating serendipity in design-driven field studies on ship bridges. *The Design Journal*, *22*(S1), 1899–1912. https://doi.org/10.1080/14606925.2019.1594948

### Publication 3

Nordby, K., Frydenberg, S., & Fauske, J. (2018). Demonstrating a maritime design system for realising consistent design of multi-vendor ship's bridges. In *Proceedings of the RINA international conference on human factors*. Royal Institution of Naval Architects.

### Publication 4

Nordby, K., Etienne G., Frydenberg S., & Eikenes J. O. (2020, August 17–19) *Augmenting OpenBridge: An open user interface architecture for augmented reality applications on ship bridges* [Virtual presentation]. 19th Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT '20). Online/virtual due to COVID-19. DOI: 10.13140/RG.2.2.15067.13607

### Publication 5

Frydenberg, S., Aylward, K., Nordby, K., & Eikenes, J. O. H. (2021). Development of an augmented reality concept for icebreaker assistance and convoy operations. *Journal of Marine Science and Engineering*, *9*(9), Article 996. https://dx.doi.org/10.3390/jmse9090996

### Publication 6

Frydenberg, S., & Nordby, K. (2022). Virtual fieldwork on a ship's bridge: Virtual reality-reconstructed operation scenarios as contextual substitutes for fieldwork in design education. *Virtual Reality*. Advance online publication. https://doi.org/10.1007/s10055-022-00655-1

## ACKNOWLEDGMENTS

First and foremost, I extend my gratitude to the Oslo School of Architecture and Design and the Institute of Design for their warm welcome during my tenure as a PhD fellow. Within this academic community, I have had the privilege of learning from a diverse group of educators, designers, and researchers. I owe special thanks to the management, research, and teaching teams at The Institute of Design, the lecturers at the PhD School at The Oslo School of Architecture and Design (AHO), and the administration and library teams for their unwavering support.

I would like to acknowledge the late Birgitta Cappelen for her invaluable support during my PhD application process, which marked the initial step of this journey.

My deepest appreciation goes to my primary supervisor, Kjetil Nordby whose dedicated support, pragmatic approach, and constructive feedback have been instrumental in navigating the complexities of my PhD journey. His ability to blend clever opportunism with rationality serves as a true inspiration for serendipitous research, extending far beyond my own endeavours. I also wish to extend a special thanks to Sigrun Lurås—my co-supervisor during the final year—for her expert guidance, engaging discussions, and unwavering support.

Further, as a member of the Ocean Industries Concept Lab (OICL), I express my gratitude to Jon Olav Eikenes, Jon Fauske, Etienne Gernez, and Sahil Mathur for their explorative, reflective, and dedicated collaboration with me. I would also like to thank Lasse Thomasgård and Rachel Troye for their contributions to design-driven field research in the Arctic. Additionally, I extend my appreciation to all current and former OICL team members, including student assistants, former students, and research advisors. Their invaluable contributions have significantly propelled OICL's research momentum, serving both as my primary research setting throughout my PhD and the subject of my study.

I would also like to express heartfelt gratitude to the students who contributed to my research during the tangible interaction course at AHO in 2020.

OICL has fostered a vast external network of outstanding resources, and I am thankful to Steven Mallam at The Marine Institute of Memorial University of Newfoundland, who served as an academic collaborator and provided structured and valuable feedback as the reader of my exegesis. I also appreciate Katie Aylward for our joint research and writing efforts during our collaboration in the SEDNA project. In addition, I owe special thanks to Odd Sveinung Hareide for his support and assistance with field access while working at the Royal Norwegian Naval Academy. I also extend my gratitude to Erik Stolterman for his expertise and enthusiasm.

I am also profoundly thankful to the users, domain experts, researchers, and designers I encountered during my PhD. Your willingness to share knowledge and insights has been indispensable. I extend special gratitude to the crew of KV Svalbard, who accommodated my research team during an incredible expedition to the West Ice in 2018.

In addition, I am grateful to my family and friends for their unwavering support. My heartfelt thanks go to my mother, Merete Frydenberg, for encouraging me to embark upon this journey and for providing me with invaluable assistance and attention in the course of this work. I also owe special thanks to my friend, Anette Iselin Hasaas, for her continuous consideration and for constantly checking in on me.

Last but certainly not least, I owe a debt of gratitude to my husband Michael and my children Aksel, Niels, and Iben—you have been my unwavering pillars of support through this long and challenging PhD journey. Your understanding, boundless energy, and abundant love have sustained me. I eagerly anticipate the new journeys that lie ahead with you all by my side.

*This thesis is dedicated to my late father, Geir Kleppan, whose serendipitous engagement with materials through art and crafts not only shaped my perspectives on formgiving but also instilled in me a lifelong appreciation for creativity and exploration.*

## PREFACE

I have always been intrigued by the state of personal flux, seeking new opportunities for self-development. Growing up in an artistic and academic family, I became aware of my explorative agency very early in life. It is important to note that this was not about being a brilliant problem-solver in the traditional sense; rather, it implies that I approached challenges differently. Instead of rigidly adhering to plans, I often relied on my intuition and had a knack for recognizing underlying patterns to navigate the complexities I encountered. In my mind, letters and numbers became intertwined with colours, music with hues, time with shapes, words with forms, and thinking with doing, ultimately translating impressions into expressions crafted through various means. While this openness to new possibilities could occasionally feel overwhelming and disruptive to established structures, it also opened doors to unexpected and serendipitous experiences.

This mindset, encompassing my sense of self, is not confined to my profession as a designer; it is also the driving force behind my exploration of serendipity in this PhD thesis. This research is more than an academic pursuit; it represents a continuum in my ongoing career. It emerges from my dedication to scrutinise the very core of design—how we make sense of and engage with the materials of complex situations to effect transformative change. This intangible yet profound process is increasingly relevant in our ever more complex world, where comprehending its procedural aspects is crucial.

Having worked as an interaction designer, both in-house and as a consultant, I have often been part of rationalising processes in which making plans, setting goals, and establishing fixed frameworks represented strict predictions regarding a complex design situation. Seeking control of uncertainty is, of course, a reasonable aim. But are we actually in control? I have observed that rather often, another force intervenes in our expectations: *the unexpected*. In the navigation of design complexity, these unforeseen consequences, unlikely coincidences, and random changes represent critical factors. Through my PhD research, I have been able to explore how these factors can be understood and harnessed by cultivating serendipity in a setting that is generous in terms of time and resources. Here, I have been allowed to employ an open and pattern-seeking mindset to research the rational, intentional mechanisms underlying such a strategy.

However, while I am clear about the values that guide this research, I am also aware of the potential pitfalls of interpretation biases. Even in this brief introduction, I have depicted personal traits as fundamental to my professional understanding of navigating complexity. Designers often rely heavily on their subjective understanding, and as such, my introspection is the subtext in this research.

## TERMS AND DEFINITIONS

| | |
|---|---|
| **Aft bridge** | The aft part of the ship’s bridge. |
| **AHO** | The Oslo School of Architecture and Design |
| **AR** | Augmented reality |
| **Case Studies** | In-depth examination of specific instances within a methodologic research framework |
| **HCI** | Human-computer interaction |
| **HMD** | Head-mounted displays (e.g. Microsoft HoloLens) |
| **HF** | Human factors |
| **IMO** | International Maritime Organization |
| **Navigator** | A person responsible for safe and accurate navigation of the vessel |
| **OB** | OpenBridge design system |
| **OICL** | Ocean Industries Concept Lab |
| **POI** | Point of interest |
| **SA** | Situation awareness |
| **Ship’s bridge** | The elevated room on a ship where the ship's navigation, control, and communication systems are located, and from which the captain and crew can oversee and manage the ship's operations. |
| **UI** | User interface |
| **UX** | User experience |
| **VRROS** | Virtual reality–reconstructed operation scenarios |
| **WCAG** | Web Content Accessibility Guidelines |

# 1 INTRODUCTION

Designing augmented reality (AR) systems for ship bridges presents formidable challenges in the field of interaction design. These challenges are rooted in the complexity of designing for an emerging technology in a highly dynamic and unpredictable context. Interaction designers are continually confronted with this form of complexity as they navigate a dynamic landscape defined by evolving technology, diverse user demands, and ever-changing requirements. Stolterman (2008a, p. 57) defines design complexity as 'the complexity a designer experiences when faced with a design situation', emphasising the multifaceted nature of this undertaking.

Over the past few decades, the design research community has displayed a keen interest in exploring how designers should approach complexity (e.g. Buchanan, 1992; Dorst, 2015b; Sanders & Stappers, 2008; Schön, 1984; Sevaldson, 2022). As a feature essential to designing, complexity is part of the designer's 'reflective conversation with the materials of the situation' (Schön, 1992, p. 5). This pragmatic concept encompasses both mindsets and approaches related to *designerly ways* of thinking and acting in the design process (Cross, 2001). To pragmatically evaluate design frameworks and methods, it is imperative to explore their application in real-world contexts (Schønheyder & Nordby, 2018).

In the context of interaction design, complexity emerges from interconnected factors, including technological advancements, the integration of multiple systems, diverse user groups, evolving design trends, and regulatory considerations. These factors give rise to a plethora of design requirements, such as usability, accessibility, aesthetics, expectations, safety, and technology goals (Cooper et al., 2014). Furthermore, complexity is compounded by the rapid technological evolution of the systems and equipment that designers shape (e.g. Höök & Löwgren, 2021). This complexity involves shaping the qualities of the interaction material, be it physical or digital (Wiberg, 2017, p. 27). However, designing with novel interaction materials—like AR technologies on ship bridges—lacks established design precedents, guidelines, or analytical frameworks (Guo et al., 2022).

This research seeks to establish practical frameworks for navigating design complexity, thereby offering insights into its dimensions, interconnections, and various design approaches. In this pursuit, complexity is analysed through the lenses of problem-solving (Funke, 2014) and decision-making (Stacey, 1996), thereby revealing key characteristics—*uncertainty, change*, and *unexpectedness*. These characteristics converge with the intriguing concept of *serendipity*, which implies the occurrence of positive events or outcomes without prediction or anticipation (Merton & Barber, 2004).

In this thesis, I specifically explore how serendipity can be cultivated within a design approach that is aimed at pragmatically navigating design complexity, thereby contributing to the evolving field of interaction design. I adopt a *practice-driven* approach in the research and employ *embedded case studies* (hereafter referred to as 'case studies') consisting of specific subcases and their interconnections, all contributing to the exploration of an overarching case (Yin, 2013). These cases delve into the design of novel interaction materials used on ship bridges, with a major focus on head-mounted display (HMD) AR technologies (hereafter referred to as 'AR'), such as Microsoft HoloLens. AR systems augment users' perception of their surroundings by overlaying real-time data and digital information, thereby providing direct access to pertinent information (Gernez et al., 2020).

Designing AR systems for ship bridges introduces numerous forms of complexity. First, ship bridges host numerous interconnected systems, operating under demanding and ever-changing conditions (Lurås, 2016a). Second, the ship's bridge environment is unfamiliar for and inaccessible to designers, thereby requiring substantial effort to understand it (Lurås et al., 2015). Third, assessing qualities such as efficiency, user experience, and situational awareness in high-risk domains presents challenges, as failure could have severe consequences for human life or lead to significant economic or environmental damage (Boll et al., 2020). Additionally, limited research and practice in AR design complicates matters, thereby hindering the establishment of design precedents (Guo et al., 2022). Lastly, the rapid technological evolution of systems and equipment necessitates a highly adaptable and flexible design approach (Ward et al., 2018).

I conducted this research in the Ocean Industry Concept Lab (OICL) through a collaboration with team members, stakeholders, and students. This PhD was incorporated in the research projects Safe Maritime Operations under Extreme Conditions: The Arctic Case (SEDNA), OpenBridge, and OpenAR. Data collection was employed through a methodological bricolage, including methods like experience prototyping, design-driven field research, development of virtual reality–reconstructed operation scenarios (VRROS), and teaching activities. Secondary data was collected by team members. The research projects leveraged VRROS to explore the design complexity of designing AR for ship bridges (Figure 1).

Section 2.1 elaborates on the contextualization of the problem statement in the case studies.

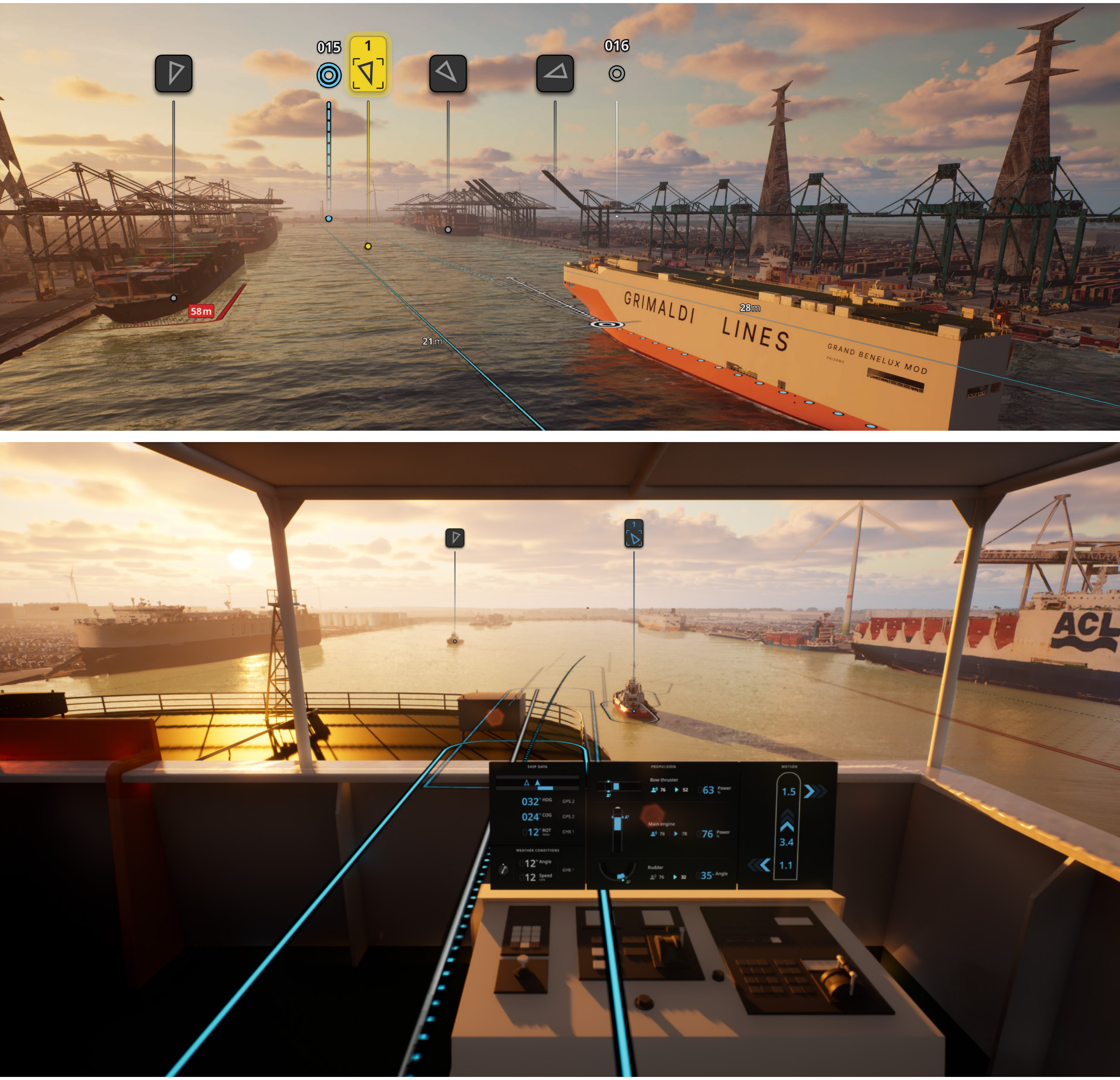



**Figure 1:** The virtual reality-reconstructed operation scenarios (2023 iteration) exploring designs for augmented reality technologies used on ship bridges designed by the OpenAR design research project. (Illustration: OICL)

## 1.1 PROBLEM STATEMENT

### 1.1.1 Research Gaps

Taken together, the previously mentioned concerns and subjects constitute a challenging void for interaction designers facing design complexity. The first three gaps address general concerns, while the fourth and fifth address case-specific concerns related to the case studies.

1. The lack of practice-led research contextualising a pragmatic methodological stance addressing and adapted to real-world complexity
2. The lack of practical frameworks for categorising and navigating design complexity in interaction design
3. The lack of research describing how serendipity can be cultivated as a means in a design approach to design complexity
4. The lack of design precedents and frameworks for AR for ship bridges to contextualise practice-led research in real-world complexity
5. The lack of methodological perspectives for the design of AR for ship bridges contextualised as case-led exploration of design complexity

### 1.1.2 Research Aim

To address the highlighted gaps, my aim was to explore opportunities for enhancing design approaches for understanding and navigating design complexity by cultivating serendipity. I adopted a practice-led, case-driven approach and evaluated within real-world settings. To contextualise this aim in practice, I specifically explored the design of AR systems for ship bridges. In this context, *practice-led research* is related to developing new understandings about practice (Candy, 2006), and *case-driven* refers to using multiple embedded cases as primary units for investigation (Scholz & Tietje, 2002; Yin, 2013). *Real-world settings* refer to the process of open innovation (Bogers et al., 2019) in a living lab (e.g. Følstad, 2008; Hawk et al., 2012) for design, as well as in the field, involving a high degree of participation from industry partners and end users.

### 1.1.3 Research Questions

In pursuit of this aim, I investigated the following research questions:

- ***How can interaction designers develop a pragmatic approach to navigate design complexity by cultivating serendipity?***

- Subsidiary Research Question 1: *What are the fundamental aspects of design complexity that interaction designers need to comprehend and address?*

- Subsidiary Research Question 2: *In what ways can serendipity be deliberately nurtured and integrated into the interaction design process to enhance sensemaking and creative outcomes?*

## 1.2 STRUCTURE OF THE THESIS

This doctoral dissertation follows the format of a 'thesis by compilation' (Morrison, 2017) and, hence, is publication-based by integrating the research work of six publications. This thesis consists of two parts:

**Part I**
Part I is the exegesis which provides a rigorous and comprehensive analysis and interpretation of the published research of Part II. This entails delving into the theoretical and practical contexts of navigating design complexity by cultivating serendipity, evaluating the applicability, and positioning it within the existing body of research.

**Part II**
Part II consists of the six publications included in this thesis.

Chapter 1 presents a general introduction to design complexity and serendipity, as well as the aim, research questions and summary of the publications. Chapter 2 serves as an overview section of the case background of designing for AR in the maritime domain, the new role of interaction design and the research projects within which this PhD was undertaken. Moreover, the chapter delves into the theoretical foundations that underpin this thesis, providing insights into my understanding of pragmatism in design, design complexity and serendipity. This chapter constitutes a theoretical framework indicating the potential relations between design complexity and serendipity. Chapter 3 provides an overview of the research approach, methods, and data analysis. Chapter 4 reports selected findings from the six publications through a conceptualisation of design complexity. Chapter 5 presents four key concepts that contextualise how serendipity can be cultivated in a design approach to design complexity. Chapter 6 situates the results presented in Chapters 4 and 5 in a broader context by discussing serendipity as a strategy, defining a complexity landscape, and discussing the applicability of the results. Chapter 7 presents the contributions according to the research questions, the transferability of the results, limitations, future research, and impact. Chapter 8 serves as a summary of the main conclusions drawn from the thesis.

## 1.3 SUMMARY OF THE PUBLICATIONS

This thesis is a result of six publications published between 2018 and 2022 addressing design complexity through case studies of exploring designs of AR for navigation and operation on Arctic ship bridges. In the following, summaries of the publications are presented chronologically. To clarify my roles in each publication, I have included a section at the end of each summary listing the contributions by author initials.

### 1.3.1 Publication 1: Exploring Designs of Augmented Reality Systems for Ship Bridges in Arctic Waters

This conference paper presents findings from two field studies related to exploring how to design AR systems for ship bridges. Both field studies were conducted in Arctic waters, with a special emphasis on Arctic operations. The aims are divided into three main categories. First, we aimed to examine what premises and possibilities needed to be integrated in the design process based on selected operation scenarios unfolding onboard. Second, by familiarising ourselves with the maritime context of a ship's bridge, we aimed to achieve a foundation for understanding opportunities. Third, we aimed to assess different interaction design methods for addressing design complexity. The field studies report on a new and complex design area with current technical immaturities, few boundaries connected to use potential and a demanding field context of shifting conditions and advanced operations to perform design work within. We describe how design-driven field studies expand designers' understanding of the context and the possibilities and limitations connected to exploring AR technology designs. We propose initial categories for challenges of using AR equipment on the bridge, placement and appearance and present examples of AR concepts. We conclude by stating the challenges connected to both the situation we designed for and AR as an immature material, but we also emphasise the potential of AR for ship bridges.

**Author Contributions**
Conceptualisation and methodology, S.F. and J.O.H.E.; software, J.O.H.E.; validation, S.F., J.O.H.E. and K.N.; formal analysis and investigation, S.F. and J.O.H.E.; resources, S.F., J.O.H.E. and K.N.; data curation, S.F. and J.O.H.E.; writing – original draft preparation, S.F.; writing – review and editing, K.N. and J.O.H.E.; visualisation, J.O.H.E. and S.F; supervision, project administration and funding acquisition, K.N.

### 1.3.2 Publication 2: Serendipity in the Field. Facilitating Serendipity in Design-Driven Field Studies on Ship Bridges

This conference paper and journal article describes the methodological approach of exploring design methods for design-driven field research in the complex and unpredictable context of a ship's bridge through a new and boundaryless technology represented by AR. This paper implements *serendipity* as a lens to investigate how the mixed methods approach combined with an opportunistic and flexible attitude towards discovering unexpected but still valuable data can accommodate design complexity. The article emphasises that planning, background knowledge, inquisitiveness, creative thinking, and time may facilitate serendipitous outcomes and proposes that a serendipitous approach is useful when exploring new design areas lacking design guidelines and precedents, such as the design of AR for ship bridges.

The methodological findings from the two field trips are presented as three selected examples of field study situations where the serendipitous approach led to unexpected and fortunate findings. Publication 2 is first and foremost a descriptive article presenting an opportunistic, flexible, and open way of considering, planning and conducting design-driven field studies. By borrowing aspects from social anthropology, the paper interprets serendipity from the designer's perspective and proposes a concrete way of conceptualising a serendipitous approach as a means in unpredictable and unfamiliar field study situations.

**Author Contributions**
Conceptualisation and methodology, S.F.; validation, S.F., J.O.H.E. and K.N.; formal analysis and investigation, S.F; resources, S.F., J.O.H.E. and K.N.; data curation and writing – original draft preparation, S.F.; writing – review and editing, K.N. and J.O.H.E.; visualisation, S.F; supervision, project administration and funding acquisition, K.N.

### 1.3.3 Publication 3: Demonstrating a Maritime Design System for Realising Consistent Design of Multi-Vendor Ship's Bridges

This conference paper explores how the complexity of multivendor bridges can be accommodated through design consistency in user interfaces (UIs). We present a proposal for how a maritime design system can be applied to form an integrated uniform ship bridge workplace. By using an iterative design process, we demonstrate the implementation of web design strategies that maintain agile possibilities for updates, extensions and customisation, such as responsive design, day light palettes, standard UI components, layout, and logics. This way, the ship's bridge can function as one integrated workplace for the end user while improving the time and cost of managing and developing software for vendors. The aim of the paper is to demonstrate how a unifying design system can contribute to better usability, efficiency and safety for both the end users and the developers by implementing important design qualities of consistency in logics, hierarchy, icons, colours, alerts etc. The proposal consists of 10 UI types designed, analysed and iterated through an experimental process with an openness to accommodate needs and changes towards establishing a gradually more complete design system. Even though this publication does not particularly concern AR, it represents a relevant part of this thesis because it exemplifies the OICL design research process by describing the incremental and iterative development of a design system for complexity. Additionally, this research introduces the seminal work – the OpenBridge (OB) design system, which is a foundation for all the research in this thesis.

**Author Contributions**
Conceptualisation, K.N. and J.F.; methodology, K.N., S.F. and J.F.; formal analysis, K.N. and S.F.; investigation, K.N. and J.F.; resources, K.N.; data curation, K.N; writing—original draft preparation, K.N. and S.F.; writing – review and editing and visualisation, J.F.; project administration and funding acquisition, K.N.

### 1.3.4 Publication 4: Augmenting OpenBridge: An Open User Interface Architecture for Augmented Reality Applications on Ship Bridges

This conference paper addresses design complexity in developing conceptual frameworks for AR design. We present an initial proposal of a UI architecture for the development of generic AR applications for ship bridges. The architecture consists of a collection of frameworks supporting the design of different aspects and information types for a selection of operational scenarios. The frameworks build on the OB design system, which seeks to facilitate the development of consistent application UIs across different vendors. Since AR is a new technological platform that can take advantage of the user's complete surroundings, few design boundaries currently exist, and design content categorisation in AR UIs is needed. We emphasise the importance of holistic design frameworks that consider the ship's bridge as an integrated workplace. Further, it is key that these frameworks are developed from iterative loops of application and generalisation to numerous case studies to accommodate change and uncertainty in a complex process. This process gives rise to serendipity by allowing the integration of new chance opportunities. We conclude that AR needs specific adaptations to maritime use and that the proposed architecture can be considered a starting point for further development and may amplify the use of AR as a branch of the OB design system.

**Author Contributions**
Conceptualisation and methodology, K.N., J.O.H.E., S.F. and E.G.; software, J.O.H.E.; validation, formal analysis and investigation, K.N., J.O.H.E., S.F. and E.G.; resources, K.N. and J.O.H.E.; data curation, K.N., J.O.H.E. and E.G.; writing – original draft preparation, K.N.; writing – review and editing, J.O.H.E., S.F. and E.G; visualisation, J.O.H.E.; supervision, project administration and funding acquisition, K.N.

### 1.3.5 Publication 5: Development of an Augmented Reality Concept for Icebreaker Assistance and Convoy Operations

This journal article addresses the complexity of designing for a high-risk maritime operation by presenting a case study of icebreaker assistance. We present the development of an AR UI concept and its evaluation in terms of design process and usability. The UI design is based on the OB design system. The development of this concept into a high-fidelity prototype to be experienced in a Virtual Reality (VR) simulator enabled exploring a wide range of chance opportunities regarding contextual and operational responsiveness in AR. This article describes a serendipitous design process consisting of design-driven field research and further development in the lab. VRROS are introduced as a novel methodological approach both for explorative design development and to perform usability studies remotely in the technology lab by using VR equipment to access a virtual scenario playing out containing an Arctic ship bridge during operation and navigation (see Figure 30 for setup). The VRROS are based on descriptive scenarios inspired by real events, such as the sinking of *MV Explorer* near Antarctica in 2007 and elaborated according to insights from several comprehensive field research expeditions aboard ice breaker vessels operating in Arctic waters. To ensure realism according to order of events and detail, the VRROS were verified by field experts. We conclude that the study presents interesting potentials for improving SA during convoy operations based on the usability study. In addition, we highlight the value of iterative and incremental development of an AR system, such as this case demonstrates, in the establishment of frameworks for design and evaluation of further research.

**Author Contributions**
Conceptualisation, J.O.H.E., K.N. and S.F.; methodology, S.F., K.A., K.N. and J.O.H.E.; software, J.O.H.E.; validation, J.O.H.E. and K.N.; formal analysis and investigation, J.O.H.E., S.F., K.A. and K.N.; resources, K.N.; data curation, K.A.; writing – original draft preparation, S.F. and K.A.; writing – review and editing, K.N. and J.O.H.E.; visualisation, J.O.H.E.; supervision, project administration and funding acquisition, K.N.

### 1.3.6 Publication 6: Virtual Fieldwork on a Ship's Bridge: Virtual Reality-Reconstructed Operation Scenarios as Contextual Substitutes for Fieldwork in Design Education

This journal article addresses complexity in terms of students' perceptions and approaches to complex user situations and design patterns. We describe a case study where we investigate the potential of VRROS of Arctic-going vessels as a methodological approach to virtual fieldwork in the education of interaction designers. The VRROS are the same as described in Publication 5. The VRROS were used as a pragmatic approach to meet the need for real design-driven fieldwork in an interaction design master course during a COVID-19 lockdown period when the students had no access to the field. The course assignments focused on addressing specific research questions through the design of AR UI components. The aim was to improve the usability and efficiency for the navigators during three different operations represented in each VRROS.

The results are based on empirical data from the students' lab work, project presentations and a questionnaire integrated into our research as action research. We evaluated if and how the VRROS could work as a substitute for working in a real user context, with the aim of understanding the physical, spatial, and temporal aspects of designing for specific operations. We discuss the potential of using VRROS as a creative and efficient technique for the exploration and testing of UI design and conclude that VRROS can work for virtual field work in selected aspects. Further, the VRROS presented promising opportunities for prototyping by offering a highly accessible context with manipulative condition settings that let the students explore a range of chance opportunities. This article is concerned with serendipity on two levels: first, the students used the VRROS to serendipitously explore chance opportunities of AR design, and second, the case of investigating the VRROS' potential for virtual fieldwork represents a serendipitous outcome in resolving the need for fieldwork during COVID-19 lockdown.

**Author Contributions**

Conceptualisation and methodology, S.F.; software, K.N.; validation, S.F. and K.N.; formal analysis and investigation, S.F.; resources, K.N.; data curation and writing – original draft preparation, S.F.; writing – review and editing, K.N; visualisation, S.F.; supervision, project administration and funding acquisition, K.N.

# 2 CONTEXT: COMPLEXITY AND SERENDIPITY IN INTERACTION DESIGN

This chapter establishes the theoretical and contextual foundation for this research. The first section presents the context of the case studies in the specialised environment of ship bridges, where I explore AR design. The studies highlight the challenges and insights gained from studying a novel interaction material in a unique setting. The second section defines my pragmatic approach to interaction design, and the third explores design complexity. The fourth section introduces serendipity as a strategy to cultivate complexity's inherent unexpectedness, setting the theoretical underpinnings for my in-depth exploration. The fifth section summarises the theoretical lens used in this thesis.

## 2.1 THE CONTEXT OF THE PROJECT

This section is dedicated to establishing a practical context for understanding design complexity and its intricate dynamics in the context of my case studies. The cases constitute integral facets of the comprehensive inquiry conducted across multiple research projects. My chosen backdrop, the ship bridges, serves as dynamic and intricate settings in which I, together with OICL team members, have examined the application of AR in real-world scenarios.

The ship's bridge environment, characterised by its high-risk and safety-critical nature, provides a unique and challenging context for my research. It is within this environment that I have sought to unravel the multifaceted characterisation of design complexity materialised as an exploration of designing for AR technology. This section aims to guide through the intricacies and nuances that emerge when integrating the innovative underexplored interaction material of AR with the rigorous demands of ship operations. My primary objective is to highlight the inherent complexities that arise when design converges with technology in a highly specialised context. Through the lens of my cases, I aim to extract valuable insights that not only contribute to the AR field but also enhance the comprehension of the multifaceted nature of design complexity.

### 2.1.1 Innovation in the Complexity Zone

The complexity paradigm encourages innovation (Dodevska & Mihic, 2014). This is typically located in the complexity zone in the Stacey matrix (see Figure 2.2 in Section 2.3.3). Within this zone, traditional management methods prove less effective, while high levels of creativity and innovation thrive, paving the way for the development of new approaches to complexity (Zimmerman, 2001). Innovation projects stand out from conventional projects due to their elevated levels of uncertainty and risk (Dodevska & Mihic, 2014). Managing innovation in this zone requires a different approach than that used for traditional projects, as innovation projects necessitate a greater infusion of creativity compared to standardised methods (Filippov & Mooi, 2010).

### 2.1.2 The OICL

My research has been conducted as an OICL member working on open innovation projects (Bogers et al., 2019). The research group collaborates closely with leading industry actors to conduct practice-led research projects that accommodate the user needs for safety and efficiency in workplace contexts, such as ship bridges, as a part of the rapid technological development in the maritime industry. This is similar to the characteristic of a *living lab* (Følstad, 2008; Hawk et al., 2012). The OICL consists of a multidisciplinary team of designers, students, engineers, and researchers and is equipped with advanced technologies for prototyping, user testing and collaboration, such as ship bridge simulators and mixed reality equipment.

The overall research method of all research projects conducted by the OICL is 'research by design', implying that design practices and methodologies are integrated as a means for inquiry and knowledge generation (elaborated in Chapter 3). The research and innovation efforts have yielded diverse outputs, including reports, conference papers, journal articles, patents, design exemplars, YouTube videos and a range of innovative solutions. The OICL has, for over a decade, applied a system approach to changing how the industry designs workplaces through an open innovation process (Strange & Nordby, 2022).

### 2.1.3 The Research Projects

My case studies have been situated within the following three research projects during the PhD period.

### SEDNA

SEDNA (June 2017–June 2020) aimed to enhance the safety and efficiency of maritime operations in the challenging Arctic environment, considering extreme weather conditions, sea ice and limited infrastructure. The project aimed to develop designs for innovative technologies (such as AR), operational guidelines and risk management strategies to support safe navigation, emergency response and environmental protection in Arctic waters. The project involved collaboration between multiple stakeholders, including researchers, industry partners and government organisations.

### OpenBridge

The OpenBridge project (2017–2022) aimed to address challenges in fragmented ship bridge consoles where various vendors provide individual system implementations. This leads to diverse interfaces, higher training needs, increased human error risks, elevated costs, and limited innovation. OpenBridge aimed to solve these problems by creating design guidelines, component libraries and an Industry 4.0 IT methodology. OpenBridge developed a maritime design system (referred to as OB design system) through maritime use cases, regulations, and multidisciplinary collaboration. The goal was to provide an efficient, consistent, and user-friendly design guideline for integrated ship bridges. The research included iterative user testing, an implementation platform and component-based documentation. After the project, OpenBridge continued development as a consortium of 40 partners (as of 2023) across the maritime industry and ship bridge vendors. The OB design system has been widely adopted and is iteratively improved. It is accessible via Figma, allowing designers and developers to download the library and create designs and front-end code, gaining significant engagement in the maritime industry.

### OpenAR

OpenAR (2022–2025) is an extension of the OpenBridge project, addressing the need for open-source design frameworks to develop AR applications for advanced maritime operation. OpenAR implements a user-centred, field-driven, iterative, and open research strategy and involves industrial partners such as Equinor, TechnipFMC, Vard Electro, Blue Ctrl, Kongsberg Maritime, the Norwegian Coastal Administration and Norwegian Maritime Authority, and academic institutions, including The Oslo School of Architecture and Design (AHO), the University of South-Eastern Norway and the University of

Bergen. OpenAR aims to foster innovation and address critical challenges such as digitalisation, safety improvement, cost-effective opportunities in the maritime industries and the design of autonomous systems and their workplaces.

Throughout my doctoral study, my primary focus has been on SEDNA's research topics. However, OpenBridge's and OpenAR's topics have been relevant for the breadth of my case studies.

### 2.1.4 Designing for the Ship's Bridge and the Oceanscape

The overarching aim of the case studies was to explore design for AR technology to be used by navigators on a ship's bridge. The ship's bridge, also known as the navigation bridge or wheelhouse, is a critical control centre on a ship where navigational, operational and safety-related tasks are performed (Woodman, 2002). It is typically located at an elevated position on the ship, providing a commanding view of the surrounding oceanscape (Figure 2). I introduced the term *oceanscape* in Publication 5, discussing it further in Publication 6, as a term helpful for defining the design space of the ocean landscape.

The bridge is equipped with various instruments, displays, controls and communication systems that enable the crew to monitor and control the ship's movement, navigate through waterways, and ensure the safety of the vessel and theirs (Figure 3). Thus, the bridge plays a vital role in maritime operations, serving as the primary workspace for navigators and officers. Navigators must continuously monitor and interpret data from radar, charts, communication systems and other sources to assess the ship's position, detect potential hazards and make informed navigational decisions (Hareide & Ostnes, 2017b).

### 2.1.5 Situation Awareness in High-Risk Environments: A Focus on Maritime UI Design

Designing for ship bridges is a critical undertaking, given the high-risk nature of the maritime industry (Boll et al., 2020). The ship's bridge serves as a complex working environment where safety-critical tasks are performed. Safety-critical systems, as defined by Knight (2002), refer to systems for which failure can lead to the loss of life, significant property damage or environmental harm. The performance of such systems can be influenced by the navigators' communication skills (Park & Kim, 2018) and situation awareness (SA) level (Sharma et al., 2019).

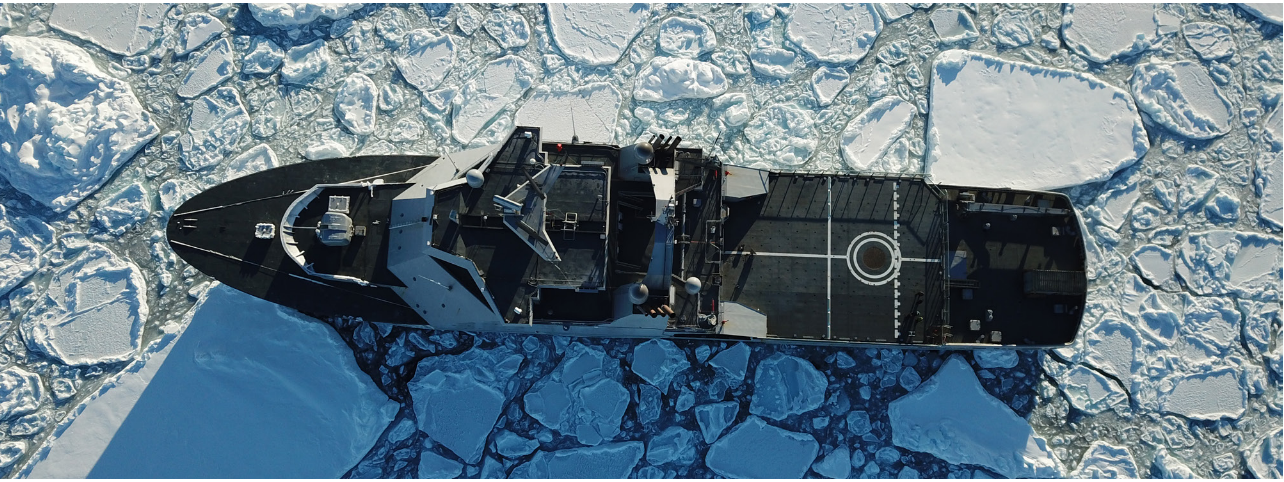


**Figure 2:** The ship's bridge of *KV Svalbard* located at an elevated position on the ship, providing a commanding view of the surrounding oceanscape. (Photo: OICL)
**Figure 3:** The bridge equipped with various instruments, displays, controls and communication systems. (Photo: OICL)

Mariners' ability to act as competent decision-makers is highly valued, making SA a core consideration in UI development for the case studies. M. R. Endsley (1995, p. 36) underscores that SA goes beyond recognising data and defines it in three levels: 'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'. In other words, perception is just one facet of creating awareness. To achieve SA, navigators must understand the integrated significance of what they perceive according to their goals. This means users incorporate SA as a perceptual foundation of the situation as a whole to inform their decision-making.

Wickens (2008) argues that SA is a crucial and valuable construct, yet it remains controversial, particularly regarding measurement issues. SA is rooted in the human factors (HF) tradition, where research standards centre around measurable assessments. However, it is crucial to note that HF and the intersecting tradition of Human-Computer Interaction (HCI) differ from interaction design in their evaluation methods. While HF and HCI often lean towards quantitative approaches, interaction design tends to prioritise qualitative evaluation methods to understand user experience (UX), preferences and behaviour. In this thesis, SA served as a foundational concern guiding the development of design heuristics, rather than as a measure for evaluating outcomes (as discussed by Schønheyder, 2019).

Designing UIs that effectively support and enhance SA requires an interaction design approach grounded in a profound understanding of what SA entails. Traditional navigation principles have historically centred around visual recognition and identification of targets, with navigators heavily relying on visual observations shaped by experience (Baldauf & Procee, 2014). However, the evolving use of advanced technology and the emphasis on efficiency have transformed the working environment for navigators (Hareide & Ostnes, 2017b). Despite the goal-oriented nature of mariners' activities, often involving extended periods of relatively low navigation activity, sudden shifts to highly complex situations requiring multitasking and a high workload can occur (Procee et al., 2017). The unpredictable nature of mariners' behaviour stems from various influencing conditions. Mariners often lack precise foresight regarding the future state they need to achieve (Cordon et al., 2017). Consequently, the situations they encounter can be diverse and idiosyncratic, prompting them to adapt their goals and objectives while on duty.

Safety at sea has markedly improved in recent decades, attributed to technological advancements, the enforcement of stringent regulations, enhanced training programmes and collaborative efforts within the maritime industry (Allianz Global Corporate & Specialty, 2021). These initiatives have resulted in enhanced vessel monitoring, improved navigation accuracy, heightened crew preparedness and the establishment of a robust safety culture. However, it is crucial to recognise that incidents and accidents still pose significant concerns within the maritime domain (Petroliumstilsynet, 2023). Designing UIs to enhance SA remains a critical imperative in high-risk domains.

### 2.1.6 Applicable Approaches for an Unfamiliar Domain

In high-risk domains such as the offshore industry, designers are increasingly involved in crafting safety-critical systems for complex and unfamiliar settings (Lurås et al., 2015). Traditionally, the offshore sector has lacked the presence of industrial or interaction designers, leading to ambiguity in roles and project scopes. Nevertheless, the industry is shifting to incorporating designers at earlier stages, engaging in more comprehensive projects. This underscores the importance of adopting a systemic approach, as outlined by Lurås (2016a, 2016b), led by practice, as suggested by Schønheyder and Nordby (2018).

However, when developing design methods supporting design practice, a gap exists between academia and practice (Dickson & Stolterman, 2016; Gray, 2016). The ever-expanding realm of technology and possibilities significantly impacts the maritime industry, necessitating the adaptation of design approaches to changing innovation landscapes. As Daalhuizen (2019) highlights, new design methods often emerge from industry and academic projects but can lose relevance in practice when methodology becomes the goal rather than a means to empower practitioners to meet evolving needs. In this context, research founded in practice becomes ever more pertinent (Davis, 2008).

Schønheyder and Nordby (2018) illustrate the practical development of design methods within a four-stage process, using a cyclic evolution model. By highlighting theoretical principles, including the primacy of practice, the apprenticeship system and the self-organising system, the authors convey how the pragmatic shaping and reshaping of design methods function in practice. However, design complexity is always rooted in specific contextual constraints that need to be collected, interpreted, and balanced in the approach.

### 2.1.7 Regulations and Requirements

Lurås (2016a) notes that the challenges designers meet when faced with projects in the maritime industry are highly complex and even 'wicked'. In addition to the domain being unfamiliar and methodically difficult to approach, designers also need to grapple with an intricate web of regulations overseen by the International Maritime Organization (IMO). These regulations, including mandatory conventions such as Safety of Life at Sea (SOLAS) (IMO, 2021), codes, resolutions, circulars and guidelines, influence designers' work, as they are constructed to ensure safety at sea (Lützhöft et al. 2011). Designers must also consider standards from organisations such as the International Electrotechnical Commission (2021) and the International Organization for Standardization (2007) and Web Content Accessibility Guidelines (WCAG) when using web technology (Web Accessibility Initiative, 2018), along with rules from ship management companies and charterers. Understanding these regulations is essential, but their complexity can overwhelm designers, leading to a perception that addressing regulations is not their responsibility (Lurås et al., 2015).

### 2.1.8 Previous Doctoral Research in the OICL

Several PhD projects at the OICL have tackled the enhancement of ship bridges and design methods for this from different angles (Gernez, 2019; Lurås, 2016a; Schønheyder, 2019). The doctoral research originated from the goal of creating an optimal bridge through systemic design, as discussed in Lurås's proposal (2016a). The research further advanced by focusing on field-driven human-centred design methods to address deficiencies in ship design processes, as highlighted by Gernez (2019). Additionally, Schønheyder (2019) explored the development of design methods for safety-critical systems in practical settings. While building on this foundational research, my work ventures into the realm of designing distributed and multimodal systems that span ships, vendors, users, locations, and technologies. This exploration contributes to a new dimension of design complexity characterised by a novel interaction material: AR.

### 2.1.9 AR Potentials and Pitfalls

AR systems have garnered substantial attention in recent years, promising to revolutionise the maritime industry by enhancing SA, improving decision-making processes and increasing operational efficiency (e.g. Baldauf & Procee, 2014; Benedict et al., 2016; Hareide et al., 2017; Hareide & Porathe, 2019; Procee et al., 2018, 2020; Rowen, Grabowski, & Rancy, 2021; Rowen, Grabowski, Rancy, & Crane, 2019). By utilising real-time data and digital overlays, AR systems provide users with relevant information directly, augmenting their perception of the surrounding environment (Milgram & Kishino, 1994). This way, navigators can simultaneously monitor what I refer to as the oceanscape and the ship bridge systems (Hareide & Ostnes, 2017b.

AR systems introduce innovative approaches to ship bridge operations, as illustrated in Figure 4 (developed in SEDNA). By using AR headsets, navigators can access contextually relevant information in their environment (Gernez et al., 2020). It is important to note that throughout this thesis, AR specifically refers to AR for HMD, mostly employed by the use of Microsoft HoloLens (Zeller et al., 2019). AR technology, especially when using HMD headsets, reduces navigators' head-down time and enhances their SA and decision-making capabilities (Hareide & Porathe, 2019). Instead of relying solely on traditional instruments and displays, AR overlays can project critical data, such as navigational routes, obstacles, and points of interest, directly onto the real-world oceanscape. The adoption of AR technology in the maritime industry has the potential to transform the way navigators work and contribute to safer and more efficient maritime operations (Laera et al., 2021).


**Figure 4:** Head–mounted display augmented reality systems, exemplified by the use of Microsoft HoloLens, introduce innovative approaches to the ship bridge operation. (Photo: OICL)

AR systems also play a significant role in the training and education of maritime personnel. By simulating real-world scenarios and overlaying instructional content, AR systems enable trainees to acquire practical skills and knowledge in a controlled environment (e.g. Lvov & Popova, 2019; Mallam et al., 2019; Markopoulos & Luimula, 2020). This approach enhances the learning experience and prepares individuals for complex tasks and emergency situations.

Designing effective AR systems for ship bridges presents unique challenges not only due to the complexity of the working environment but also due to the lack of established design guidelines and precedents for AR systems (Ashtari et al., 2020; Grabowski, 2015). Unlike other industries, such as aviation or automotive, the maritime domain lacks standardised design principles tailored specifically for AR systems on ship bridges (Guo et al., 2022), making it challenging for designers to create intuitive, user-centred AR UIs that seamlessly integrate into the existing bridge infrastructure.

To overcome these challenges, a comprehensive approach is necessary. Designers must consider a wide set of existing requirements when designing systems for ship bridges (e.g. IMO, 2021). Requirements related to ergonomic aspects are particularly important to ensure that AR displays and controls are easily accessible without impeding crew movement or visibility (Rowen, Grabowski, & Rancy, 2021). Additionally, cognitive ergonomics in the design should address issues of information overload and cognitive load, as crew members need to process a vast amount of real-time data (Guo et al., 2022). Interdisciplinary collaboration with maritime experts and usability testing, iterative prototyping, and user feedback are essential in refining and improving the design (Aylward et al., 2021a).

### 2.1.10 AR as a New Interaction Material

AR is a location-based technology that is visualised in situ (Bressa et al., 2022). Thus, I suggest that interaction designers' understanding of the context, as part of the material of the situation, requires considering it a part of the guidelines (von der Au et al., 2023). Existing AR guidelines (mainly provided by Apple and Google) can simply be superficial experiences, as Ashtari et al. (2020) reports in an interview study. The study participants further argued that the guidelines fall short in addressing the complexity and ambition of designers by focusing mainly on simple, single-scene applications, lacking support for interactive features, complex mechanics and scene transitions using teleportation. Across different fields, the need for AR design guidelines is highlighted, spanning from the evaluation of AR collaboration (Marques et al., 2022; van den Oever et al., 2023) to guidelines to enhance design in architectural education (Milovanovic et al., 2017) and ethical guidelines for AR in workplaces (Greene, 2022).

AR is a versatile technology that finds applications in various fields, including gaming, education, design, navigation, and remote collaboration. Given the diverse range of contexts in which AR is employed, the development of guidelines becomes not only crucial but also highly *context specific* (Sag, 2018). This implies that AR, along with the specific context in which it is utilised, can be viewed as a new *interaction material* (Wiberg, 2018). Nordby (2011) proposes the term *conceptual material* to define a material approach to technology by emphasising that designers shape the effect of technology rather than the technology itself. The material view on AR can empower designers to shape the impact and influence of technologies rather than merely focusing on the technologies themselves.

As an interaction material, AR provides designers with a unique opportunity to create experiences and interactions that align with the specific goals, needs and constraints of each context (Lindlbauer et al., 2019). I argue that *context-specific guidelines* should consider the particular requirements and considerations of each application domain. For instance, guidelines for AR on ship bridges might emphasise aspects such as enhanced SA, intuitive controls, and seamless integration of virtual elements within the oceanscape. By recognising AR and its application context as part of the material designers give form to, it is possible to go beyond the technical aspects and consider the broader implications and possibilities – 'a reflective conversation with the materials of the situation' (Schön, 1992 p. 5).

However, the repertoire of design methods, tools, examples, design patterns and design systems interaction designers use in a common design process have developed from a screen-based design tradition (Preece et al., 2015). When designing UIs for screens, interaction designers focus on optimisation for a two-dimensional display, such as a computer or mobile device screen (Moggridge, 2007). In contrast, when working with AR, interaction designers need to consider how the user will interact with digital information in a three-dimensional, physical environment (T. Endsley et al., 2017). Summarising the AR guidelines from Microsoft (2022) and Apple Developer (2023), designers must note that AR UIs adapt to the user's physical surroundings, assess spatial awareness, embrace more natural gestures and inputs and strike a balance between relevant AR content and the real-world context to minimise distractions.

Consequently, the development of design guidelines and best practices specifically tailored for AR systems on ship bridges is necessary to facilitate the seamless integration of this transformative technology into the maritime industry (e.g. Ashtari et al., 2020; Grabowski, 2015). This PhD thesis explores the intertwined complexity between the intricate requirements for designing for the maritime domain and the interaction material of AR used in the ship bridge environment as method to contextualise design complexity in general. To do this, I will, in the next section, establish my stance on the field of interaction design.

## 2.2 THE LANDSCAPE OF INTERACTION DESIGN

The field of interaction design is in a constant state of evolution, with numerous approaches shaping its landscape. In this subsection, I articulate my viewpoint on interaction design by presenting the ideas and principles that underpin my stance. Central to my exploration is a fundamental question: *What does it entail to design for interactions between humans and systems?* To address this question, I first outline my perspectives on the interaction design field and its practice. These perspectives draw from my extensive practical experience in interaction design and my background in industrial design.

### 2.2.1 Interaction Design and User Experience

Interaction design is a discipline within the design field which is dedicated to crafting meaningful and captivating UX in both digital and physical settings (Moggridge, 2007). The term was coined in the mid-1980s by Bill Moggridge, the designer of the first laptop computer and founder of IDEO, in collaboration with HCI researcher and designer Bill Verplank. However, it took another decade for this concept to achieve widespread recognition (Cooper et al., 2014). In this thesis, I adopt Löwgren and Stolterman's (2007 p. 5) formal definition: 'Interaction design refers to the process that is arranged within existing resource constraints to create, shape, and decide all use-oriented qualities (structural, functional, ethical, and aesthetic) of a digital artefact for one or many clients'.

Mainly rooted in industrial design and HCI (Löwgren, 2014), interaction design is closely tied to the technological advancements of digital systems, such as web services. Interaction design is considered a relatively new field compared to other disciplines and is still characterised by rapid development (Winograd, 2006). In the web industries, interaction designers engage with numerous adjacent fields, with fluid borders described (Saffer, 2010). This includes *information architecture*, which involves the structural design of shared information environments (Resmini & Rosati, 2011); *user interface (UI) design*, focused on the process of creating visual and interactive elements of a software application, website or product that users interact with (Stone et al., 2005); and *UX design*, which centres on the overall experience that users have when interacting with a product or system (Norman, 1988).

UX has gained prominence in recent decades as a response to the dominant usability paradigm, which primarily focused on task-related aspects (Hassenzahl & Tractinsky, 2006). UX encompasses the user's emotions, thoughts, sensations and actions throughout an activity, with a focus on comprehension derived from user research (Benyon, 2019). This aligns with the core objective of interaction design, which is to deeply comprehend users' needs for tailored solutions (Löwgren & Stolterman, 2007).

Contemporary interaction design methods prioritise empiricism, emphasising the importance of designing *with*, rather than *for*, users (Sanders & Stappers, 2008). This approach also underscores the significance of understanding users' relationships with the systems they are part of (J. C. Jones, 1992). These methods, suggesting that a suitable design solution can emerge through a thorough examination of the current scenario, has proven successful and forms the foundation for practical and concept-driven design processes (Stolterman & Wiberg, 2010). However, the heightened emphasis on use context and design impact has raised dematerialisation concerns in the design process. These concerns are compounded by capitalism's drive for streamlining and automation (Kelly, 2018) and, more recently, the imminent challenges posed by AI and machine learning (Matthews et al., 2023). In addition to the focus on UX, designers also need to adapt their processes to meet complex challenges of technological development (Meyer & Norman, 2020), which can be understood as complex systems (Buchanan, 2019). These technological systems are what designers shape, and as such, they can be understood as the materiality of interaction design (Wiberg, 2018).

### 2.2.2 A Material Perspective on Interaction Design

In the realm of interaction design, the way designers give form is intricately linked to the specific material being used, including technology as a material encompassing physical or digital substances (Giaccardi & Karana, 2015). Höök and Löwgren (2021) outline three significant ways in which digital artefacts are reshaping the terrain of interaction design. First, they argue that interaction design predominantly involved crafting custom software to run on conventional hardware, frequently centred around glass screens. Today, we are pushing beyond these constraints, exploring hybrid materials that seamlessly bridge the physical and digital realms. Second, the authors state that digital objects were typically standalone products, each with a distinct value proposition and well-defined design specifications, adhering to strict delivery schedules. Presently, every project unfolds as an unpredictable intervention within a dynamic digital ecosystem, fostering intricate relationships with a multitude of digital services and hardware platforms. Third, they note that traditional digital tools were often viewed as predictable instruments for instrumental purposes. However, the advent of AI and machine learning has introduced the concept of partially autonomous systems. These systems exhibit evolving behaviours and capabilities that adapt usage patterns over time. This way, I find that Höök and Löwgren underscore the continually changing landscape of materiality in the field of interaction design, urging the adoption of new perspectives.

Defining and articulating the concerns of giving form to interactive artefacts becomes crucial, especially when dealing with intangible, flexible, temporal and changeable phenomena often associated with interaction design (Löwgren & Stolterman, 2007). Interaction is a dynamic interplay between the user and the interactive artefact, where the holistic UX goes beyond visual appearance (Bertelsen & Pold, 2004; Fiore et al., 2005). Löwgren and Stolterman introduce the concept of *interaction gestalt.* This pertains to the comprehensive and unified experience of engaging with a designed system or interface, encompassing various attributes (e.g. connectivity, continuity, directness) that shape this experience (Figure 5; Lim et al., 2007). In this context, attribute refers to specific qualities or characteristics that contribute to the overall experience of engaging with a digital artefact.

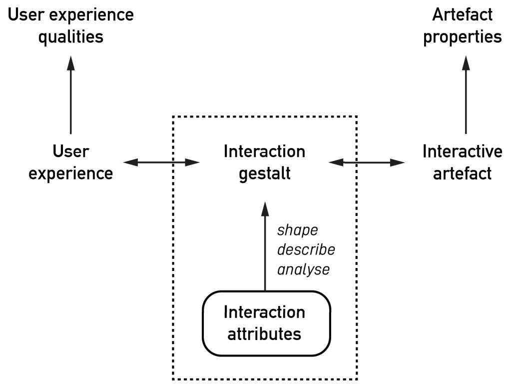



**Figure 5:** The interaction gestalt (Lim et al., 2007) redrawn by Frydenberg, S. in 2023.

Translating these attributes into the interactive artefact is essential for creating a meaningful and impactful UX (Löwgren & Stolterman, 2007). While the subjectivity of UX implies that we cannot design it directly, focusing on the qualities of these attributes is crucial. The discussion around technology as a material has gained relevance in interaction design – with a 'material turn' occurring in the field, necessitating new terminology for describing digital structures (Robles & Wiberg, 2010). Wiberg (2018) suggests that a material-centred process can help explore interaction design through the material aspects and dimensions. The unlimited possibilities of technology challenge traditional categorisations (Löwgren & Stolterman, 2007). However, exploring designs through material-specific approaches can be a useful approach, exemplified in the case study of RFID technology as a short-range material (Nordby, 2010). Akin to this, I suggest that the case studies can offer a situated material perspective to better understand the complexity of the process.

### 2.2.3 Pragmatism: Situated Inquiry

In design practice, there is a significant emphasis on addressing a particular problem – the situation at hand (Stolterman & Wiberg, 2010). To gain a deeper understanding of interaction design, I find it useful to leverage theories from a broader field, of which design can be considered a subset. Dewey's pragmatic philosophy emphasises the fundamental role of situations in shaping human thought and action (Dalsgaard, 2014). Nelson and Stolterman (2014) describe situations as contextual wholes – which, according to Dewey (1938b), comprise subjects, artefacts, social constructs and physical surroundings. Building upon Dewey's ideas, Schön's (1984) reflective practice approach highlights the situated nature of design. By viewing design as a reflective conversation with the materials of the situation, Schön (1992) argues that designer's perceptions of the environment are part of the materials shaped while practicing design. Through experiencing different environments through different cases, practitioners develop a repertoire of methods, skills and expectations (Schön, 1984), and by studying concrete cases within their design paradigm, they are 'thinking from exemplars' (Kuhn, 1979, p. 305). This implies that practitioners learn through situated inquiry by generalising the knowledge into principles applicable to similar cases. Dewey (1938b) defines situated inquiry as 'hermeneutical gaps' between the existing situation and the desired outcome, necessitating interpretation and creative problem-solving to bridge the gap between these two forms of understanding.

Dewey's century-old ideas remain pertinent, emphasising the unpredictable, ever-changing nature of the world (Dixon, 2020). Instead of despairing, Dewey emphasises courage and the capacity to effectively navigate this dynamic world (S. Brinkmann, 2013). Moreover, the ongoing evolution of pragmatist inquiry underscores a shift away from conventional understandings of knowledge, placing increased emphasis on experiential learning and pragmatist inquiry, a viewpoint shared by several scholars (Chiapello & Bousbaci, 2022; Dalsgaard, 2014; Rylander Eklund et al., 2021). Grounded in Dewey's principles, pragmatism can furnish a philosophical foundation that welcomes diverse viewpoints and underscores the practical results in the realm of design (Dalsgaard, 2014) and thus becomes a valuable means of proficiently addressing design complexity (Kumar, 2012).

From my viewpoint, interaction design is a dynamic interplay of form and function, aesthetics, and usability. It is a discipline where creativity converges with user-centred principles, giving rise to seamless and meaningful digital experiences. With a clear foundation of my stance, my objective has been to set the stage for the subsequent sections that delve deeper into the intricacies of my research.

## 2.3 COMPLEXITY IN DESIGN

Having anchored my perspective within the landscape of interaction design in the preceding section, I will now address complexity as a cornerstone in design and as a fundamental aspect of my research.

### 2.3.1 Complex Design Problems

Norman (1988) defines design problems as the gaps between the current state and the desired outcome of a product or service, emphasising the need for user-centred design to create functional, intuitive and desirable solutions. Complex design problems encompass *ill-structured problems* (Simon, 1973), often referred to as *wicked problems* (Rittel & Webber, 1973), which lack clear criteria for evaluating solutions and have unclear problem spaces. These problems are challenging to comprehend until a solution emerges (Buchanan, 1992).

Schön (1984) underlines the significance of *problem setting*, the process of defining or framing a problem, in conjunction with problem-solving. He contends that professionals, such as designers, often encounter situations in the real world where the problem lacks a clear definition, necessitating a reflective process to clarify and reframe the problem (p. 40). This perspective aligns with Dewey's (1938b) pragmatic insights, emphasising the contextual nature of problems with a consideration for elements such as individuals, objects, social constructs and physical environments. Consequently, the need for a completely defined design problem becomes less critical (Dorst, 2006). In simpler terms, the design process thrives within what Schön calls a paradoxical or 'messy' situation. The essence of this process becomes apparent at a specific stage and is discernible solely through the actions and expressions of designers (Schön, 1984).

### 2.3.2 Defining Complexity

Complexity in design is a term used in various often poorly defined contexts. In this thesis, I use the term design complexity, defined by Stolterman (2008, p. 57) as 'the complexity a designer experiences when faced with a design situation' presenting a qualitative view influenced by factors such as culture and personal preferences. The term complex finds its origins in the Latin root plectere, which means 'to weave' or 'entwine' (Mitchell, 2011, p. 4). Likewise, complexity often harks back to its Latin origins – where *complexus* (derived from *complecti*) combines *com* and *plectari*, signifying 'ply' or 'braid' (Cooke-Davies et al., 2007, p. 51). This etymology indicates complexity generally signifies the composition of many parts, and it presents challenges in comprehending the relationships among these components. Funke (2014, p. 186) proposes six features that characterise complex problem-solving situations that I will present in relation to design.

### Intransparency

In complex problem-solving situations, certain variables can be directly observed, while others remain opaque. We often only perceive knowledge pertaining to the outward manifestations or 'symptoms' of the problem, necessitating deduction of the underlying state. This lack of transparency is referred to as *intransparency*. Another form of intransparency occurs when there is a multitude of variables that can be assessed, necessitating the selection of a few key ones. For example, designers working with design for ship bridges describe the volume of information necessary to process to achieve the needed insight as challenging to grasp and, thus, emphasise setting boundaries as key (Lurås et al., 2015).

### Polytely

'Polytely' refers to the occurrence of multiple goals in complex problem-solving situations. It gets problematic when some of these goals are contradictory, necessitating the need for compromises. For designers, the number of requirements for designing can constitute paradoxes in the design situation that needs to be prioritised and balanced to be resolved (Dorst, 2006; Schön, 1984).

### Complexity of the Situation

Complexity of the situation pertains to the quantity and intricacy of identification and regulation processes. A complex problem-solving situation encompasses a multitude of variables, intricate connectivity patterns, system control options and dynamic elements, potentially overwhelming the problem solver's limited capacity. Lurås (2016b) argues that the complexity of a design situation can be considered a system. By using a systemic perspective on complexity, we can gain the understanding needed to develop satisfactory solutions.

### Connectivity of Variables

A high level of interconnectivity characterises situations where alterations in one variable influence multiple related variables. Complex problems often exhibit extensive connectivity, making it exceedingly challenging to foresee all potential consequences stemming from a given situation. When designing AR for ship bridges, the connectivity of variables becomes crucial. For example, an AR system can overlay navigational charts, weather data and instrument readings onto the physical environment, with changes in one variable directly influencing others. Thus, I suggest that designers must ensure accurate and seamless integration of these interconnected variables to enhance SA and decision-making for ship navigators.

**Dynamic Developments**
Complex problem-solving situations frequently undergo decremental and deteriorating changes, compelling prompt action from the problem solver within significant time constraints. Conversely, spontaneous shifts in the opposite direction are possible, reducing stress but making the situation less predictable. To exemplify this, design-driven field research on ship bridges contextualise a work situation for designers characterised by unpredictability and change, resulting in high complexity (Lurås, 2016a).

**Time-Delayed Effects**
Not every action yields immediate consequences; instead, effects often manifest with a delay over time. Consequently, designers must exercise patience, in stark contrast to situations demanding immediate action as mentioned earlier. In a design approach, this aspect is also useful for describing delay in designers' interpretation of cues from the environment forming our perceptions and judgements about the case. Multiple studies have demonstrated that unconscious processes can contribute to creativity during *incubation* (Ritter & Dijksterhuis, 2014), which is regarded as a favoured subject in serendipity research (see, e.g., Busch, 2022a; McCay-Peet & Toms, 2015).

Summarising these definitions and features, I propose three key characteristics of design complexity (Table 1), which I later use to establish a theoretical framework for investigating design complexity (Section 2.5).

| Concept | Description |
|---|---|
| Unexpectedness | Events or outcomes occurring without prediction or anticipations. It is the quality of surprise individuals experience in deviations from norms or expectations. |
| Uncertainty | The lack of complete knowledge or information about a situation, event, or outcome. It indicates doubt or unpredictability regarding the future or the accuracy of specific information. |
| Change | The act of transformation from one state to another. It encompasses modifications, alterations or shifts in various aspects, either gradual or sudden. |

Table 1: Three Key Characteristics of Design Complexity

### 2.3.3 Complexity Frameworks

Several frameworks seeking to capture complexity have been developed across disciplines – for example, *five layers of complexity* (Kaplan, 2020) and the *Cynefin framework* (Snowden & Boone, 2007). I find the *Stacey matrix* (Figure 6), proposed by organisational theorist and management professor Ralph Douglas Stacey (1996, p. 47), especially relevant, as it is a contingency model for decision-making in complex adaptive systems. Stacey identifies two dimensions of complexity: *certainty* (predictability of events) and the degree of *agreement* (over those events). The matrix categorises decision-making situations into five different zones.

**Simple (1)**
Close to agreement, close to certainty. This zone is operated by technical rational decision-making; previous experience is relevant to predict the future.

**Complicated (2)**
Far from agreement, close to certainty. This zone is operated by political decision-making centred around negotiation, compromise and dominant coalitions to set the direction.

**Complicated (3)**
Close to agreement, far from certainty. This zone is operated by judgemental decision-making by logical incrementation.

**Complex (4)**
Far from agreement, far from certainty. This zone is operated by pragmatic approaches involving creativity and abduction in the search for new modes of operating.

**Chaos (5)**
This represents a zone of massive avoidance and is often used in reference to moving towards ‘the edge of chaos’, marking the border between Complexity (4) and Chaos (5).

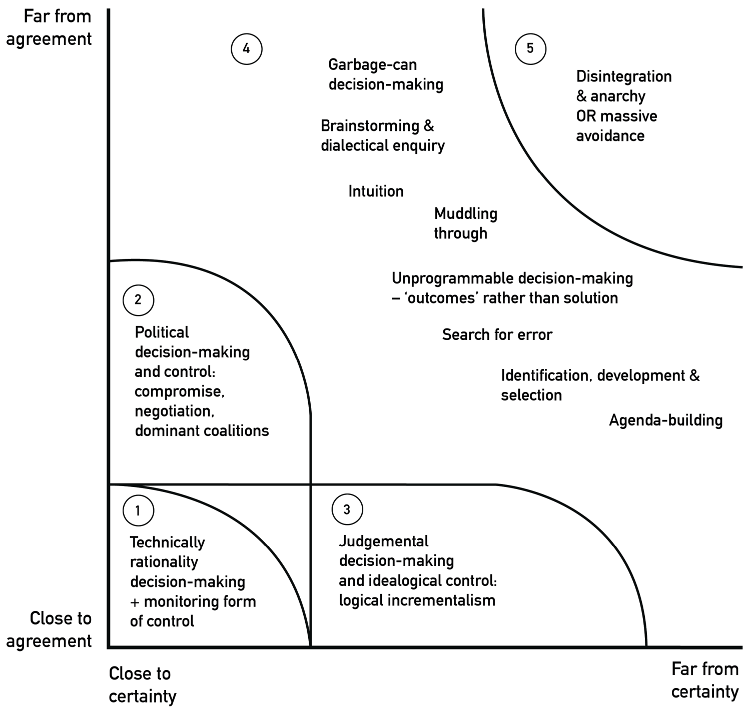



**Figure 6:** The 'Stacey Matrix' which explores the relationship between change context and decision-making/control modes (Stacey, 1996 p. 47) redrawn by Frydenberg, S. in 2023.

Originally designed to address organisational change, this matrix has been adapted in various domains, including Agile methodologies to evaluate project complexity and choose appropriate Agile practices (e.g. Poth et al., 2020). Combining Agile with design thinking, the matrix works as a tool for decision-making on customer centricity (Zierock et al., 2023). I propose that the matrix is valuable for comprehending design complexity by offering a framework to categorise varying degrees of complexity and uncertainty in design projects. It aids designers in making informed decisions, customising their approaches, and adeptly addressing challenges associated with design complexity. Nevertheless, for direct application to design, additional refinement and contextualisation of the two dimensions are necessary. This is further addressed in Chapter 4.

### 2.3.4 Approaches to Complexity in Design

Complexity approaches tend to be discussed according to the categories of reductionism and holism. In general, reductionistic approaches simplify complex systems, breaking them into smaller components (McCoy, 2009). The risk might be overlooking interactions and emergent behaviour. Holistic approaches, in contrast, examine systems as interconnected wholes, focusing on relationships and interactions and offering an alternative perspective on complex systems exemplified in theories such as network theory, chaos theory and complexity theory (Deutsch, 1998). Here, factors such as connections, sensitivity to initial conditions, nonlinear interactions and emergent properties are key considerations. In my view, such approaches might risk not delving deep into specific areas, potentially leading to a lack of specialised expertise gained through a hands-on engagement with the materials of the situation.

In design, *systems thinking* and *systemic design* are approaches used to address complex challenges comprehensively and holistically. Systems thinking, rooted in the philosophy of interconnectedness, emphasises understanding the relationships among various components within a system to devise effective solutions (Nelson & Stolterman, 2014). It acknowledges the intricate web of connections, where changes in one part of a system can trigger far-reaching impacts on others. Systemic design, on the other hand, encompasses design methodologies that integrate systems thinking principles into the design process (P. H. Jones, 2014). This approach aims to create designs that exhibit sustainability, resilience and adaptability by recognising the intricate interplay of the systems they operate within.

Vink (2023) contends that the prevalent practice of creating visual system maps in systemic design, despite its intention to be inclusive, contradicts the emphasis on the pluralism of perspectives. Specifically, techniques such as gigamapping and ZIP analysis (employed by Systems Oriented Design at AHO [Sevaldson, 2022]), while being defined as systemic approaches rooted in design practice, often present static, top-down views of systems. It is crucial to acknowledge, however, that both systems thinking and systemic design are dynamic fields lacking a unified consensus or standardised key concepts, frameworks and methodologies (Nelson, 2022). In the light of Vink's critique of the potential pitfalls of visual systems maps, a pragmatist approach becomes particularly relevant.

### 2.3.5 Designerly Ways of Thinking and Acting

Pragmatism assumes a pivotal role in design research, with a clear focus on the practical outcomes resulting from beliefs, theories and actions (Dixon, 2020). Unlike adopting a rigid stance favouring either holism or reductionism, pragmatism involves a critical evaluation of these approaches, emphasising their real-world effectiveness. Renowned pragmatists such as Dewey and Schön have stressed that the merit of any perspective should be assessed based on its ability to yield practical solutions, address specific issues and produce tangible results (Dalsgaard, 2014). Consequently, amid complexity, pragmatism permits the flexible adoption of either a holistic or reductionist approach, contingent upon what proves most effective in comprehending and managing intricate systems or circumstances.

Taking a pragmatic viewpoint, design fundamentally operates as an interventionist discipline, aiming to create concepts, artefacts and environments that actively shape designers' perceptions and behaviours (Dalsgaard, 2014). Stolterman (2008), along with fellow design researchers, strongly advocates for the refinement of the design discipline's distinctive methods and inquiry theories (Buchanan, 1992; Buxton, 2007). This is often encapsulated within the framework known as a *designerly way* of thinking and acting (Cross, 2001). Stolterman's assertion that 'design disciplines, such as interaction design, have to develop and foster their own designerly approach for education and practice' (p. 63) underscores the pressing need for design to cultivate a distinct paradigm alongside the realms of science and art (Cross, 2006). This designerly tradition, harmonising with the pragmatic viewpoint, offers invaluable insights into the nuances of situations, emergence and interaction within the domain of designing interactive artefacts (Dalsgaard, 2014). Notably, both design and pragmatism converge in their shared emphasis on the primacy of practical action over theoretical dogmas.

Building upon this discourse, Y. Rogers (2004) emphasises the need for a comprehensive exploration, identifying areas rich in conceptual depth and design articulation in both research and design practice. Designers draw upon their tacit knowledge (accumulated through extensive experience and practical application), providing them with a holistic and intuitive perspective when tackling design challenges (Rust, 2004).

Stolterman (2008) contributes a compelling perspective on how designers should engage with design complexity, advocating for *disciplined* and *rigorous* engagement in a designerly manner. This stance challenges the misconception that design is a wholly subjective and irrational endeavour. Instead, it underscores that design inherently possesses its own internal structure, procedural methodologies, and essential components. While design has not fully evolved into a formalised intellectual discourse like science, its unique tradition for designerly knowing, thinking and acting can be regarded as a distinct paradigm (Cross, 2006).

Scholars such as Buxton (2007) and Krippendorff (2005) have underscored the disciplined nature of designerly behaviour. This is grounded in practices such as sketching, which entails a rational approach to problem exploration (Kolko, 2010; Moggridge, 2007). The nature of this rationality in addressing design complexity remains a topic of ongoing debate (Schaathun, 2022). Discussing this, Schaathun suggests that Coyne (2005) conducted a comprehensive examination of various viewpoints on this matter, while Simon (1990) proposes mathematical models borrowed from the scientific domain, treating real-world issues as intricate variations. In contrast, Schön (1984) takes a different stance, emphasising the exploration of implicit epistemology within professional practice, which encompasses both artistry and intuition. He also acknowledges the existence of hidden rational processes capable of uncovering truth, ultimately seeking a comprehensive epistemological framework.

Furthermore, Y. Rogers (2004) suggests that designers indirectly harness theoretical concepts, conceiving them as *affordances*. These theoretical concepts are subjected to transformation, further development or outright rejection, contingent upon their suitability and relevance to the practice of design (Dalsgaard, 2014). This interweaving of theory and practice in design leads to iterative phases of reflection both within and upon action (Schön, 1984). Thus, Stolterman (2008) posits that designers necessitate specific methods and approaches that not only prepare them for actions but also guide them through the act itself.

### 2.3.6 Design Abduction: A Guiding Reasoning Pattern

At the core of the epistemological framework underpinning designerly ways of knowing and acting is a fundamental reasoning process known as *design abduction* (Dorst, 2015a). Abductive reasoning, originally introduced by the pragmatist philosopher Peirce (1958), serves as a method for generating and exploring potential explanations or hypotheses when confronted with challenges. Sometimes referred to as *productive reasoning* in design (March, 1976), abductive reasoning places a significant emphasis on the practical and experiential aspects of the design process. It empowers designers to make well-informed decisions, even in situations with incomplete information, thereby fostering iterative problem-solving processes (Dorst, 2011, 2015b). Design abduction encourages designers to maintain openness to alternative perspectives, consider multiple solutions and adjust their approach based on feedback and reflection. These principles closely resonate with the pragmatic values of experimentation, adaptation, and practicality.

| ??? | + | ??? | leads to | VALUE |
|---|---|---|---|---|
| (WHAT) | | (HOW) | | |

**Figure 7:** An abductive reasoning pattern for complexity as described by Dorst (2011).

Dorst (2011) suggests that when designers grapple with complexity, abductive reasoning can be depicted as a logical equation that involves the unknown 'WHAT' and 'HOW' to arrive at a 'VALUE' when framing design problems (illustrated in Figure 7). This process of abductive reasoning stands apart from the more conventional inductive and deductive forms and is sometimes likened to a generalised form of intuition in design thinking (Cross, 2023). This perception may contribute to the notion of the design process as unstructured, as observed by Stolterman (2008). However, this specific reasoning pattern is indispensable for the inherent quality of *emergence* in design. As Cross (2023, p. 11) notes, 'relevant features emerge in tentative solution concepts and can be recognised as having properties that suggest how the developing solution-concept might be matched to the also developing problem-concept'. This notion of emergent features within design aligns with the broader understanding of abduction – often referred to as 'inference to the best explanation', which underscores the role of explanatory reasoning in justifying generated hypotheses (Douven, 2021).

According to Dorst (2011), a hypothesis represents the 'working mechanism' or 'HOW' in the abductive equation. In the context of constructive design research, the development of design hypotheses begins with a clear motivation, followed by the formulation of a more specific research question and the establishment of evaluation criteria (Bang et al., 2012). Hypothesis testing takes the form of experimentation where competing hypotheses are assessed to favour one over the others (Schön, 1984). Design experiments conducted beyond the controlled research setting, such as rough-tech experience prototyping in design-driven field studies described in Publication 1, can provide support for the validation or rejection of assumptions and decisions upon which a hypothesis is founded

(Binder & Redström, 2008). This validation is based on exposure and the perception of extended cues in the environment.

### 2.3.7 Making Sense of Complexity

In the domain of design, designers frequently grapple with incomplete information when confronted with complex design situations. They rely on sensations and heuristics to make sense of their environment (Yilmaz & Seifert, 2011). Sensemaking assumes a critical role in design (Krippendorff, 2005) and is integral to understanding complexity within the framework of pragmatism (Dewey, 1925, 1938b) and psychology (Weick, 1995; Weick et al., 2005), as well as in Schön's (1984) insights.

Design is often perceived as a method for structuring complexity by harmonising requirements and shaping them into a coherent structure (Kolko, 2010). However, synthesis fundamentally entails a cognitive process aimed at organising and elucidating data or information to foster comprehension. In the design process, this cognitive endeavour is externalised through giving tangible form to ideas. To substantiate and communicate their rationales, designers commonly employ various techniques to visualise their thought processes, such as gigamapping (Sevaldson, 2022), the Cynefin framework (Body & Terrey, 2019) or a conceptual design for sensemaking (Blandford et al., 2014).

Nonetheless, it is essential to recognise that sensemaking is an embodied, situated practice deeply intertwined with the act of creation in design (Schön, 1984, 1992). In creative professions, individuals often 'act to think' (Weick, 1998, p. 547). Consequently, the actions and creations may erroneously appear as if they are merely oriented towards problem-solving without a discernible rationale (Stolterman, 2008). However, this type of sensemaking constitutes problem-finding (Verganti et al., 2020).

Sensemaking can be seen as an ongoing mental process where designers continuously update their understanding as they gather more information and experience, as discussed by Lurås (2016b). She proposes a systemic model of the design situation, which offers a framework for understanding the systems that designers are influenced by and that designers themselves influence in the design process (p. 39). The model considers three interconnected systems: 1) *the system we design* refers to the objects or products that designers create; 2) *the system we design for* relates to the context in which the designed product will be used, encompassing factors such as users, tasks, equipment; and environmental conditions; and 3) *the system we design within* includes the factors that shape designers' ability to work effectively, including industry- and project-specific factors, as well as the designers' own organisations. The model reveals how interconnected systems in a design situation are essential for successful design and how design choices can impact the broader system conditions.

### 2.3.8 Brunswik's Lens Model: A Cognitive Perspective on Sensemaking

Sensemaking holds similarities to the idea of understanding how individuals make judgements and decisions based on cues or proxies in the cognitive psychology theory of perception developed by Egon Brunswik (1935). Brunswik (1943) proposes that a person perceives the environment through a *lens*, meaning a set of imperfect cues, and acts accordingly. In other words, he posits that that an individual's understanding of the world is like putting puzzle pieces together – it is not a perfect match but more like finding clues that help us figure out what is out there. To explain his idea, Brunswik (1952) created a diagram illustrating how cues from the environment help people draw conclusions, called the 'lens model'. Although originally developed to study human perception, the lens model was later recognised as a framework for social judgement theory (Hammond et al., 1975).

The key principles guiding the lens model is the notion that perception is based on multiple imperfect cues and it is not a direct match with the environment, making it *probabilistic*; for instance, designers often deal with incomplete/uncertain information or an overload of information in the design situation (Lurås et al., 2015). Hence, they employ forms of sensemaking based on design heuristics (Yilmaz & Seifert, 2011), bias (Hallihan & Shu, 2013) and mental models (Johnson-Laird, 2004) to interpret cues. This aligns with Schön's (1984, pp. 274, 317) notion of drawing on a 'repertoire of exemplars' in practice.

Further, Brunswik (1952) emphasises that *error* is unavoidable in perception because it relies on unreliable cues and that there will always be some mistakes, even when using many cues. This error is a normal part of how perception works, and hence, failure is considered an important part of innovation (Petroski, 2013). Moreover, the environment provides *redundant cues* – meaning that different cues may convey similar information about an object's characteristics, improving reliability. In this sense, it is pertinent to suggest that multiple overlapping cases and multiple team members may increase the quality of perceptual decisions in the face of uncertainty and variability. Finally, Brunswik advocated that experiments should reflect *real-world conditions* and include *various cues* rather than relying on highly controlled lab settings to capture the richness and complexity of information. In this context, Scholz and Tietje (2002) suggest that the lens model provides a framework for knowledge integration in case studies. Since case studies is the main methodology of this PhD thesis, I found this model to have a potential value in capturing the cognitive process of cultivating serendipity further explored in Concept #1: cultivating a serendipitous mind (Section 5.1).

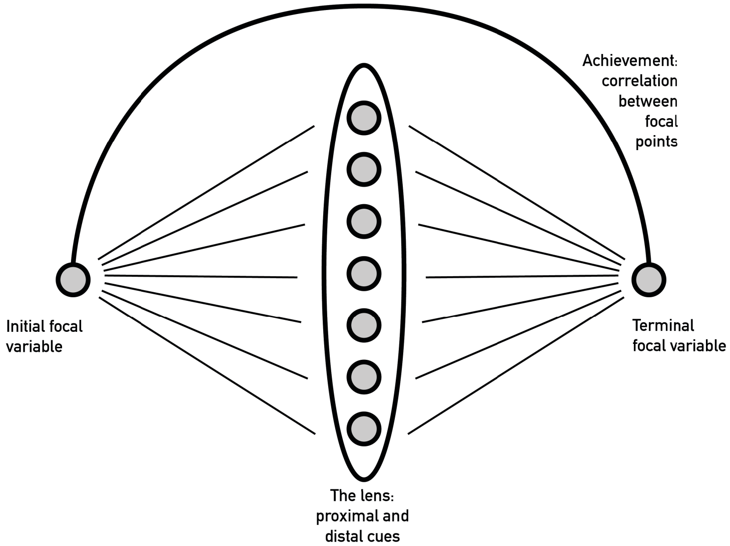



**Figure 8:** The Brunswik's lens model (1952) redrawn and simplified by Frydenberg, S. in 2023.

The lens model (Figure 8) consists of the following components which I contextualise in my own research methodology of case studies:

### The Right Focal Point

The right focal point explores the decision-maker's (designer) use of perception of cues in making decisions. For example, what are the premises and how to categorise them?

### The Left Focal Point

The left focal point explores the starting point or input in the cognitive process (a case study) and its associated cues (e.g. existing systems, environmental conditions and user responses).

### The Lens

The lens consists of both proximal and distal cues.

**Proximal Cues**
Proximal cues are those that are directly observable or perceived by an individual in the given context. These cues can be sensory information, measurements or visual observations made by the decision-maker.

**Distal Cues**
Distal cues are usually inferred or estimated based on the available proximal cues. Distal cues are often more abstract and represent characteristics of the external world that are not directly observable. For instance, the actual size or distance of an object which one cannot directly perceive is a distal cue inferred from proximal cues such as the visual size and perspective.

**Achievement**
Achievement refers to the degree of correlation between the judgement-maker's utilisation of cues and their ability to comprehend the distal variable, which in this case is the situation being studied.

The lens model offers a multilevel investigation into decision-making (Hammond & Stewart, 2001). At the first level, the focus is on examining the cues utilised for decision-making, including their format, quality, presentation, and context. The second level delves into the decision-maker's characteristics and the rules they employ. The final level, the output or decision level, assesses the decision's effectiveness, its alignment with expectations, the accuracy of cues in predicting outcomes and the decision-maker's ability to learn from the decision for future improvements. The lens model illustrates the reliance on multiple cues for making informed judgements and highlights how the redundancy of cues enhances the reliability and accuracy of decision-making (Wolf, 2005). I propose that the lens model can serve as a valuable tool for addressing design complexity by acknowledging the probabilistic nature of perception in uncertain and unexpected situations.

## 2.4 SERENDIPITY: THE POTENTIALITY OF UNEXPECTEDNESS

While navigating the intricate landscape of design complexity within the context of the case studies, an intriguing phenomenon emerges – unforeseen encounters with the unexpected. In this section, I turn to the compelling interplay of complexity and serendipity in the design process. This section presents an in-depth examination that extends beyond the structured boundaries of design complexity. It centres on the intersection of complexity and serendipity, paving the way for new possibilities in design thinking. Serendipity, often hailed as the art of making fortunate discoveries by accident, bears a striking resemblance to the unexpected nature of design complexity. Hence, I delve into the notion that in the pursuit of innovative solutions and creative design, unanticipated insights and discoveries can be cultivated. This section serves as an overview of relevant serendipity research to form a theoretical lens used to explore how serendipity can be cultivated within the structured framework of the design process, especially within the context of design complexity.

### 2.4.1 Chance as a Conceptualisation of Unexpectedness

Humans seem to have an urge to plan and control their lives by constructing procedures, process and rules applied to everything, from the smallest routines to how the structure of society (Busch, 2020). Designers strive to systemically and holistically approach problems in a rigorous and disciplined manner (Buchanan, 2019; Stolterman, 2008). However, innovation thrives in the complexity zone – characterised by *uncertainty, change* and *unexpectedness*, as established in the previous sections. These are critical unavoidable factors that shape design processes and outcomes.

In this sense, the concept of *chance* often appears as central to how designers perceive the world. Chance is a topic inexhaustible for reflections and experiments intending to understand its meaning. For example, 'luck' is interchangeably used with chance to explain being at the right place at the right time and is associated with stories of success (Csikszentmihalyi, 2013). Further, chance can describe 'stumbling upon' something – for example, 'stumble data' (S. Brinkmann, 2014) or 'gifts of chance' (S. Brinkmann, 2020). As occasion or opportunity, chance is often expressed as 'chance events' (Glăveanu, 2022) or 'chance encounters' (Copeland, 2022). Moreover, taking a chance is a central subject related to decision-making and risk-taking, and a person's willingness or tolerance for risk in taking chances is also considered a personal trait within psychology (Joseph & Zhang, 2021). Taking chances is also related to timing, which describes 'the ability to select the precise moment for doing something for optimum effect' (Merriam-Webster, n.d.-b).

In epistemological discussions, the focus on chance is related to probability and the ability to predict or know the outcomes of chance events. Some philosophers, such as Arthur Schopenhauer (2016), have argued that chance events are genuinely unpredictable, in the sense that they have no underlying causes or determining factors that can be known or understood. Other researchers have taken a different approach, suggesting that while chance events may appear to be unpredictable, they can be understood in terms of probability (Lewis, 1980). Probability theory is a mathematical framework enabling predictions regarding the likelihood of specific events transpiring, notwithstanding the unavailability of precise outcomes beforehand (Debnath & Basu, 2015). Another key question in epistemological discussions of chance is how we can come to know about chance events. Some philosophers, such as David Hume, have argued that chance events are not real, objective features of the world but rather a product of ignorance about the underlying causes of events (Harris, 1966). For example, we may not be able to perceive all the factors that contribute to a chance event, or we may not have enough data to make reliable predictions about its likelihood.

In creativity, chance often plays a central role. As opposed to science, where chance involves an unplanned fortuitous discovery, Copeland (2022) argue that creative chance is about giving form to something in a way that produces an unintended result. However, if the role of chance is an important part of creativity, it contradicts the notion of creativity as a mere 'epistemic virtue' but rather as an intersection with unexpectedness (Ross & Vallée-Tourangeau, 2021). Hence, it becomes clear that the perception of chance extends beyond objective occurrences, delving into the realm of subjectivity and interpretation. Whether recognised as an unplanned occasion, a stroke of luck or an opportunity to take action, chance finds itself deeply rooted in the human psyche. These varied interpretations of chance emphasise its role as a catalyst for both introspection and creative exploration.

### 2.4.2 The Concept of Serendipity

Studies have shown that 30–50 percent of major discoveries and innovations in science is a result of chance, derived from coincidences or failure (Denrell, 2003; Dunbar & Fugelsang, 2005). Breakthroughs, spanning from Viagra to Velcro, have therefore been explained as *serendipity* (Roberts, 1989): 'the faculty or phenomenon of finding valuable or agreeable things not sought for' (Merriam-Webster, n.d.-a). Serendipity has been considered an 'esoteric word' since it was absent from all condensed dictionaries until 1951 (Merton & Barber, 2004). While its original meaning has been extended to encompass occurrences spanning from plain ordinary to adventurous extraordinary, it is also referred to as a 'slippery concept' (Makri & Blandford, 2012). However, all the interpretations are linked to happy accidents in people's lives and in the worlds of academia, science, business, and culture.

Serendipity, as highlighted by Vuong (2022 p. 77–89), is deeply intertwined with human survival and progress. This skill of recognizing valuable information in one's surroundings, crucial for survival, has been shaped by serendipitous encounters throughout history. Moreover, Vuong (2022 p. 68–73) underscores that serendipity's influence on innovation is evident across time, from the discovery of fire to crucial medical breakthroughs, exemplified by its recent role in expediting vaccine development during the COVID-19 pandemic. With a remarkable 196,000 results on Google Scholar (as of October 2023), serendipity exhibits broad relevance and interpretations across various disciplines, making it a potent force in shaping human experiences and advancing the boundaries of knowledge and innovation (Fink et al., 2017).

### 2.4.3 Chance Favours the Prepared Mind

'Blind luck' alone cannot explain serendipity, as if human thinking and acting does not matter when facing something unexpected (Busch, 2022a). The recognition of the prepared mind's role in serendipity stretches far back in time to the Roman philosopher Seneca, who is often attributed with the statement, 'Luck is what happens when preparations meet opportunity'. Seeing luck as an expression of serendipity aligns with the English writer and art historian Horace Walpole, who coined the word serendipity in a letter to a friend in 1754, explaining it as accidental sagacity (Merton & Barber, 2004, p. 2). Sagacity, referring to the quality of being wise and discerning or showing good judgement, is a foundation for the prepared mind (Glăveanu, 2022). By increasing the likelihood of recognising and capitalising on serendipitous discoveries or opportunities (Vantomme & Crassous, 2021), the notion of the prepared mind derives from the French chemist and microbiologist Louis Pasteur (Vantomme & Crassous, 2021). His famous quote about chance favouring the prepared mind emphasises the interplay between preparedness and chance after discovering scientific breakthroughs such as the penicillin in 1928 (Vallery-Radot, 1911). When the mind is well prepared through knowledge, expertise and a deep understanding of a specific domain, individuals are more likely to notice and appreciate unexpected connections, patterns or insights that may arise by chance (Glăveanu, 2022). To conceptualise serendipity, I have defined two key components of serendipity (Table 2).

| Concept | Description |
|---|---|
| The Prepared Mind | This refers to an individual's state of readiness, often achieved through knowledge, experience and curiosity, which allows them to recognise and make use of unexpected opportunities or insight. |
| Chance | Chance encompasses the unpredictable and unforeseen events or circumstances that occur outside of one's control and can lead to serendipitous discoveries or occurrences. It involves random or coincidental factors that align favourably with a prepared mind. |

Table 2: Two Key Components of Serendipity

Seifert et al. (1995) argue that the perspective of the prepared mind does not necessarily attribute instances of insight to mysterious or extraordinary mental abilities. Instead, operating under the assumption that insight is an attainable cognitive phenomenon, this viewpoint aims to understand how insight can arise from the interplay of various information-processing stages, wherein the collective interactions facilitate subconscious leaps leading to the creation of novel mental concepts.

### 2.4.4 The Serendipity Conundrum

However, seeking serendipity constitutes a well-acknowledged conundrum (e.g. Cunha, Clegg, & Mendonça, 2010; Cunha, Rego, et al., 2015; Smith & Lewis, 2022): *how can one be prepared for the inherently unexpected?* Two distinct research approaches have emerged in the study of serendipity (Olshannikova et al., 2020). The first explores *natural serendipity*, characterised by its unpredictable and nonfacilitated nature (Vuong, 2022). Studies have investigated spontaneous encounters in creative fields (Copeland, 2022). Liestman (1992) refers to the idea of the prepared mind as 'intuitive sagacity'– meaning a random collection of ideas containing loose information capsules that, through an external cue, can be rearranged in a form of perspicacity. In other words, obtaining a broad form insight from which the right information can be retrieved at the right time to form new knowledge is a general form of preparing the mind when building sagacity.

The second approach focuses on what is called *artificial serendipity* (de Melo, 2018) or *serendipity by design* (Reviglio, 2017). This involves the use of artificial agents, such as ICT applications, to facilitate or trigger serendipitous experiences. This line of research aims to design systems that promote chance encounters (e.g. Erdelez, 2004; McCay-Peet & Toms, 2010; 2015). In the domain of information retrieval and interaction design, artificial serendipity is exemplified by content-based recommender systems that enable surprising and novel discoveries by implementing random mechanisms to endow the user's serendipitous experience when interacting with rich data sets, such as music players, search engines and web shops (Liang, 2012). The direct control of serendipity is challenging due to its inherent unpredictability, leading to a paradoxical nature when attempting to intentionally plan such unplanned experiences (Van Andel, 1994). There is a limited empirical foundation for providing practical guidance to designers on how to design UX that incorporates serendipity (Makri et al., 2014).

### 2.4.5 Serendipity in Design of Information Technology

Serendipity, long overlooked, is now acknowledged as a vital design principle within the realm of information technology (Reviglio, 2019). To promote serendipitous discoveries, digital products can be designed for meaningful unexpectedness through interaction design (Liang, 2012). Although the two elements of serendipity, whether called *accident* and *sagacity* or *chance* and *prepared mind*, is agreed upon across research fields, their interconnection, their subcomponents, the process, and the subjectivity are widely debated. Working as a cipher open for interpretation (Merton & Barber, 2004), serendipity has been modelled and defined in numerous ways.

McCay-Peet and Toms (2015) have evaluated four empirical models (see Makri & Blandford, 2012; McCay-Peet & Toms, 2010a; Sun et al., 2011; V. Rubin et al., 2011) in the field of information systems exploring serendipity in everyday life and research. Based on an analysis of these models, evaluated in an interview study, McCay-Peet and Toms (2015) suggest a model of seven elements: 1) trigger is about noticing a cue that initiates the experience of serendipity; 2) delay describes the time between the trigger and making the connection; 3) connection is the recognition of the trigger's relevance according to existing knowledge; 4) follow-up describes acting upon the connection to achieve some sort of serendipitous value; 5) valuable outcome is the serendipitous effect materialised; 6) unexpected thread describes the chance present in either 1, 3, 4 or 5; and 7) perception of serendipity describes the experience of serendipity.

Serendipity in digital information environments has been discussed according to several concerns. New and useful information can be discovered through the use of digital tools or technologies (Maxwell et al., 2012). For example, a user might use a search engine to find information on a topic of interest and then stumble upon new and relevant information they did not know existed. This 'aha' moment can lead to new ideas and insights and help users expand their knowledge and understanding of a particular subject (Makri & Blandford, 2012). In this context, serendipity is considered an end, *an outcome* (Fine & Deegan, 1996), shaped by both environmental and human elements, and it encompasses crucial stages of information production, distribution, and consumption (Reviglio, 2019). Designing information architectures to foster serendipity involves enhancing the variety of encountered information and granting users greater control over information processes (Makri & Blandford, 2012). Recognising the importance of serendipity in the discovery process, computer scientists have endeavoured to create systems that foster and promote serendipitous encounters (André et al., 2009).

Serendipity is also considered a skill that individuals can promote, employing strategies that heighten the likelihood of serendipitous experiences (Denrell, 2003). This way, the focus is on serendipity as *a means* to achieve the outcome (Smets, 2022) or on applying those skills in the *process* (e.g. Makri & Blandford, 2012; McCay-Peet & Toms, 2010b; Reviglio, 2019).

### 2.4.6 Serendipity as a Strategy

With the aim of approaching design complexity serendipitously, it becomes essential to view it from a strategic standpoint. Recognising chance opportunities is just the first step; knowing how to effectively seize and capitalise on them is what transforms them into serendipitous discoveries (Copeland, 2022). This relates to Busch's (2022b) notion of the *materialisation* of serendipity. To achieve this, it is necessary to strategically shape both the environment and one's mindset, creating pathways that enable acting upon those chances.

The study of *creativity* delves into the underlying processes of exploring the unknown (Beghetto, 2019). It represents an important quality in interpreting new information (Busch, 2022b). Regarded as a key competence for designers in product innovation development (Lavery, 2006; Sarkar & Chakrabarti, 2011), creativity describes the production of 'something original or worthwhile' (Sternberg, 2011, p. 479). When serendipity is connected to innovations, it is similar to the 'creative leap' towards an innovation and is often the triggering cause (Cross, 1997; Kingdon, 2012). Creative thinking plays a crucial role in serendipity and design, as it enables individuals to manipulate their environment and context strategically (Copeland, 2022). According to Cross (2003), successful expert designers rely on certain *strategies for creative thinking* by 1) adopting a broader *systems approach* instead of approving a restricted problem definition; 2) *framing the problem* in a unique and, at times, personal manner; and 3) using *first principles*, a problem-solving method in which one breaks down a complex problem or concept into its most basic, fundamental components and then builds up a solution or understanding from there rather than relying on assumptions or past experiences. Seen in the light of a serendipitous approach, all three strategies also require a form of inquisitiveness and openness to go beyond the perceived frames of the problem (Cross, 2023; Dorst, 2015b). This way, the strategies represent a pragmatic perspective towards experimental and situated inquiry (Dalsgaard, 2014).

Nevertheless, it is difficult to draw a direct line between what is an individual strategy, a skill, a capability, and a personal trait in scrutinising the notion of the prepared mind in a serendipitous approach. In reviewing research aiming to articulate and elaborate on this, I found a broad set of related concepts. For example, people with an *active attention* (Cunha, Clegg, & Mendonça, 2010) or *alertness* (Agarwal, 2015) might be more likely to react by surprise, as in 'Aha!' *Curiosity* (Åkerström, 2013) or *inquisitiveness* (Rivoal & Salazar, 2013) describes the tendency of breaking behavioural patterns to learn from and engage with people and recourses across hierarchies and structures (Bardone, 2013; Bardone & Secchi, 2017). Moreover, *intuitive reasoning* is a prerequisite for flexibility in a serendipitous exploration (Rivoal & Salazar, 2013). Together with *improvisation* and *spontaneity*, it constitutes the core elements of serendipitous exploration of materials (Piñeyro, 2022).

*Generative doubt*, considered a combination of *openness* and *preparedness*, is a way of responding to change (Cunha, Rego, et al., 2015). *Framing* focuses on how one understands and defines a problem situation (e.g. Dorst, 2015b; Rauch & Ansari, 2022), while *analogue thinking*, akin to 'thinking from exemplars' in science (Kuhn, 1979, p. 305), can be transferred to the use of an existing design repertoire to new problems or situations (Schön, 1984). Moreover, temporal aspects such as *perseverance* (J. H. Austin, 2003), *making time* to increase the likelihood of serendipitous encounters (Rivoal & Salazar, 2013) and *being at the right place at the right time* are essential for being exposed to external triggers (Ross, 2022). Finally, *social skills* (Busch & Barkema, 2022a), *cognitive flexibility* (Björneborn, 2017; Busch, 2022b; Piñeyro, 2022), *reflexivity* (Rivoal & Salazar, 2013) and *self-efficacy* (Busch, 2020; Lutz et al., 2017) are important aspects of serendipitous social interaction.

However, exploring these qualities isolated from the context they are applied to does not fully describe how serendipity can be cultivated in design practice. In practice, interaction designers work in multidisciplinary teams (Fallman, 2008), and practical knowledge and theoretical understanding are shared through a spoken material-oriented tradition (Schön, 1984). However, team strategies cannot be viewed separately from higher-level strategies (Valkenburg & Dorst, 1998). Design projects are always part of a larger organisational context in intersection with other values, goals, or motives, which potentially create tensions that affect the design team or the individual designer (Löwgren & Stolterman, 2007). As a response to the call for in situ research on professional design practice (Goodman et al., 2011), I suggest that the *cultivation* of serendipity also hinges on mechanisms at the organisational level.

### 2.4.7 Cultivating Serendipity

Cultivating serendipity can be regarded as a learning opportunity in viewing organisations from an organismic perspective, acknowledging the unpredictability of the organisation's external environment and its serendipitous potential (Busch & Grimes, 2023; Cunha & Berti, 2023). In a systematic review of serendipity research, Busch (2022b) utilises insights from sensemaking, event-based theorising and quantum-based management to propose a conceptualisation by modelling the cultivation of serendipity as a multilevel process consisting of 1) *individual-level catalysts* in the form of detection and linking qualities corresponding with several of the capabilities mentioned in the section above, 2) *individual-level inhibitors and enablers* in the form of inhibiting (e.g. self-censoring) and enabling qualities (e.g. self-efficacy) and 3) *organisational-level inhibitors and enablers* in the form of resource (e.g. effective evaluation) and social integration mechanisms (e.g. social embedding).

*Resource integration mechanisms* depend on the attentional, informational, and material resources applied to the integration process (Busch & Barkema, 2022a). Organisations employ various strategies to evaluate and invest in emerging ideas systematically (Napier & Vuong, 2013). Strategic agility involves swiftly and flexibly pursuing significant change in various areas and is crucial when a company identifies new strategic prospects through serendipity (Santos & Williamson, 2022). As organisations transition from mechanistic to organic structures, as exemplified by the Agile paradigm (Birkinshaw et al., 2021), they aim to attain the flexibility to adapt to unforeseen circumstances, thereby reducing costs associated with change (Cunha & Berti, 2023). Originating from the Agile manifesto (Back et al., 2001), Agile design science research (Conboy et al., 2015) and software development might have, despite their critiques (Ozkan, 2019), a serendipitous potential combined with user-centred, practice-led design approaches in accommodating change and uncertainty (Zorzetti et al., 2022). However, Agile methods are commonly designed for *software development–led* processes, and the integration of interaction or UX design is not supported in the main methods (Plonka et al., 2014). Hence, the role of UX design in Agile processes is debated (e.g. Cajander et al., 2022).

*Social integration mechanisms* arise from the skills and interactions of multiple individuals in group settings that foster meaningful interactions and diverse perspectives (Busch, 2022b). This is facilitated by social embedding (Busch, 2020) and collective adaptive problem formulation (Cunha & Berti, 2023; McCay-Peet & Toms, 2010b), together enabling the emergence of unexpected ideas. This process is further enhanced by social integration mechanisms such as psychological safety (Edmondson & Mortensen, 2021), allowing individuals to freely share ideas without fear of negative consequences (e.g. Cunha, Rego, et al., 2015; Edmondson, 2018). However, it can also be hindered by power dynamics and politics within organisations (R. D. Austin et al., 2012). Both organisational- and individual-level factors directly and indirectly influence the emergence of serendipity in organisational contexts, highlighting the interconnectedness of organisational dynamics and individual contributions (Busch, 2022b).

Based on analysis of the reviewed literature, I have defined four key characteristics of cultivating serendipity (Table 3) that form a foundation for my theoretical framework in this PhD thesis.

| Concept | Description |
|---|---|
| Being attentive to Serendipitous Cues | Being aware of or receptive to unexpected or chance events, information or signals that could lead to valuable discoveries |
| Recognising Serendipitous Patterns | Identifying recurring themes, connections, or trends within seemingly random or unrelated occurrences, which may point to unexpected opportunities or insights |
| Seizing Serendipitous Opportunities | Taking a proactive action when serendipitous events or discoveries occur, leveraging them to achieve specific goals or create positive outcomes |
| Creating Conductive Conditions for Serendipity | Establishing an environment and fostering a mindset that encourages the occurrence and integration of serendipitous events and insight, such as through open collaboration, diverse perspectives, or exploratory activities |

Table 3: Four Key Characteristics of Cultivating Serendipity in Design

### 2.4.8 Knowledge Gaps in Serendipity Research

My review of serendipity research unveiled diverse interpretations and applications of this intriguing phenomenon. Serendipity's elusive nature makes it a subject of deep fascination across disciplines, challenging traditional thinking and revealing unexplored opportunities. Through my review, I identified three primary research areas that intersect with the unpredictability inherent in design complexity and serendipity. First, within the realm of information technology design, there is a notable emphasis on designing for serendipity as a desired UX. This suggests an avenue for further investigating serendipity as a *means* in the design process. Second, in the context of creative design processes, serendipity often centres on individual experiences. However, this focus could be expanded to explore its role in *collaborative design efforts*, emphasising design as a collective endeavour. Third, when considered from an organisational perspective, serendipity is conceptualised as a multilevel theory. This viewpoint presents an opportunity to empirically *apply serendipity theory to design practice*, adding depth to the discipline. Upon investigation of these areas, it becomes apparent that there are intriguing knowledge gaps to be addressed. Further exploration is needed to unlock the full potential of cultivating serendipity within the context of design and design complexity. This is addressed in Concepts #1–4 in Chapter 5.

## 2.5 A THEORETICAL FRAMEWORK

I find the idea of exploring the conjunction of unexpectedness within design complexity and serendipity interesting, especially because interaction design has increasingly developed a demand for new ideals dealing with an accelerating development of technology. Therefore, it is relevant to explore how interaction design can benefit from integrating a pragmatic and serendipitous approach towards design complexity, informed by practice-driven research.

In this chapter, I have established my stance on interaction design and conducted a review and analysis of both complexity and serendipity as concepts understood in the light of the field. The examination revealed a notable gap in the practical conceptualisation of design complexity which designers need for making sense and decisions and approaching projects in practice. Additionally, I observed a lack of design precedents and methodological development, including tools and approaches, to aid interaction designers in crafting UIs for complex technologies and domains, fostering innovation through the translation of materials into UX. Exploring serendipity research, I also highlighted the research gap concerning the cultivation of serendipity as a strategy for designing in interaction design. I further emphasised the potential of harnessing the unexpectedness inherent in design complexity through cultivating serendipity.

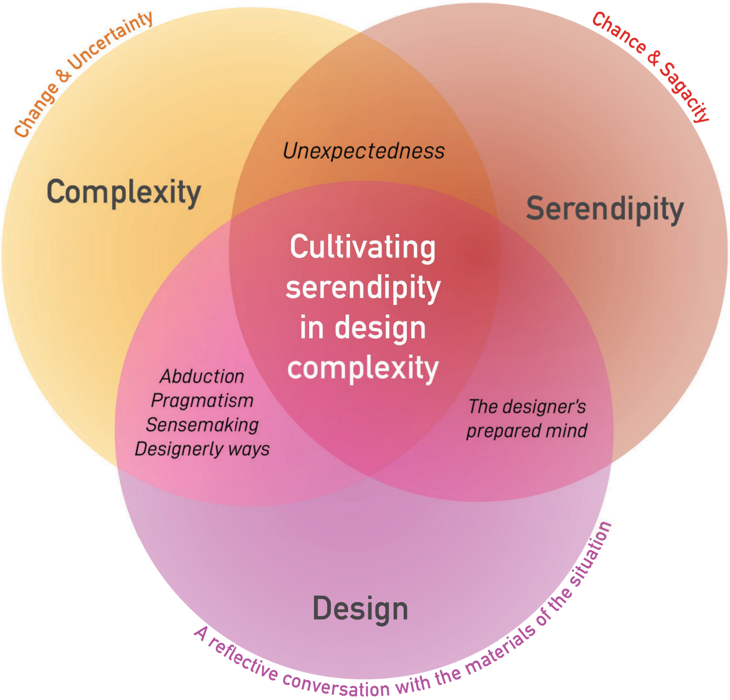



**Figure 9:** Theoretical Framework for Navigating Design Complexity by Cultivating Serendipity.

The theoretical framework for navigating design complexity by cultivating serendipity presented in this chapter defines the key concepts, key characteristics, and conjunctions within this research (Figure 9).

**Concept 1: Design**
Design is defined through a pragmatic stance as 'a reflective conversation with the materials of the situation' (Schön, 1992 p. 5). This is also in line with *Designerly ways of thinking and acting*. Moreover, *abductive* reasoning and *sensemaking* is emphasised as central for navigating design complexity.

**Concept 2: Design Complexity**
The three key characteristics of design complexity are defined as *Unexpectedness, Uncertainty* and *Change* (Table 1, Section 2.3.2)

**Concept 3: Serendipity**
The two key components of serendipity are defined as *The Prepared mind* and *Chance* (Table 2).

This framework provides a lens through which I interpreted findings and determined the underlying mechanisms at play. Moreover, it places my research within the broader context of prior research. In the next chapter, I will elaborate on the research methodology, methods, tools, and techniques I selected to address these identified gaps.

# 3 RESEARCH APPROACH AND METHODS

In this chapter, I provide an overview of the research methodology employed, beginning with a brief introduction to the approach of practice-led, concept-driven, and hands-on research by / into design. This sets the stage for discussing the knowledge developed within this thesis. Subsequently, I delve into my research strategy of embedded case studies, facilitating an in-depth examination of the phenomenon of serendipity and the concept of design complexity within the setting of exploring the design of AR for ship bridges. Through the design of a methodological bricolage, I present the various methods employed. Moreover, I describe the process of analysis and synthesis of the case study data through the development of design hypothesis. Finally, I provide an overview of the process of knowledge integration and theory development in this thesis.

## 3.1 RESEARCH BY AND INTO DESIGN

Over the last three decades, artists, designers and craftspeople have taken on the pioneering role of *practitioner-researchers* within academia (Mäkelä & Nimkulrat, 2011). They conduct academic research by integrating it into their creative practice. This concept finds its origins in Christopher Frayling's (1993) work, which categorised design research into three distinct types. The first type, research *into (about)* design, involves studying the design process, outcomes, and their impacts. It is more similar to traditional forms of research and can include academic research and critical analysis of design work. The second type, research *through (by)* design, involves conducting research as an integral part of the design process itself. It emphasises experimentation and iteration during the process. The third type, research *for* design, refers to the process of gathering information and insights to inform and guide the design process. It is often considered a precursor to the actual design work.

In my research, I employed both research by and into design. By employing a case study research methodology, I conducted research by design to contextualise my overarching and more abstract research questions. This approach places a strong emphasis on creative practice, highlighting the significance of the designer and the designing process (Stappers & Giaccardi, 2017). My PhD research was situated within SEDNA and the broader framework of the OpenBridge and OpenAR initiatives. I leveraged several case studies from these projects to provide context for my own research; that is, I conducted research by design to perform the case study research. However, my research questions, which represent an overarching investigation into how interaction designers can develop a pragmatic approach to navigate design complexity by cultivating serendipity, embody research into design. Consequently, these two research approaches worked together in a complementary manner (see Figure 10).

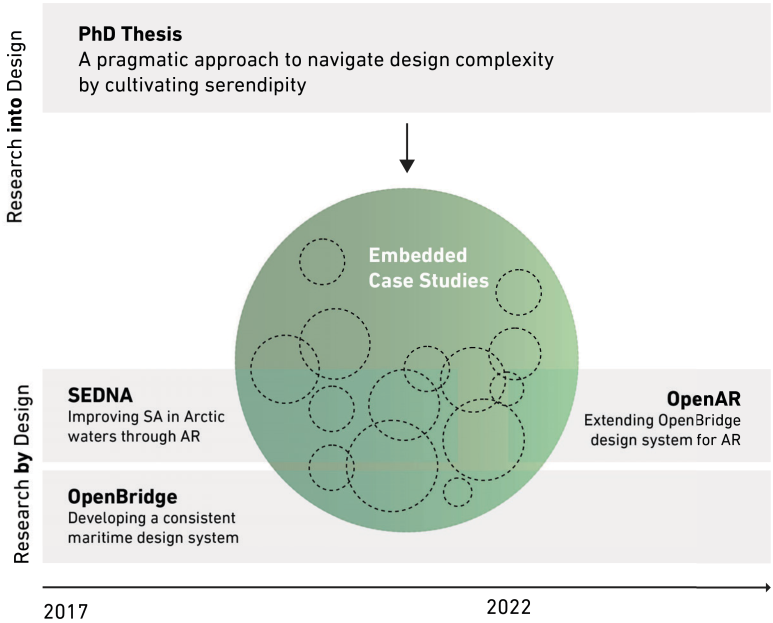



**Figure 10:** Research into Design and Research by Design Contextualised in the Research Approach of Embedded Case Studies.

Design research encompasses various terms used interchangeably, such as ‘practice-based’, ‘practice-led’ and ‘artistic research’. While artistic research integrates artistic practice and research to generate knowledge (Klein, 2010), practice-based and practice-led research focus on creative artefacts or new understandings about practice, respectively (Candy, 2006). My research primarily revolves around practice – resulting in practical insights for the field and implying, according to Candy, that it is practice-***led*** design research. I combined practice-led design research and research by design – creating a comprehensive approach which has expanded the landscape of design research, with practitioner-researchers documenting, contextualising, and interpreting their creations and processes (Mäkelä & Nimkulrat, 2011). It involves iterative cycles of design and research, each informing and enriching the other. The goal is to create design exemplars and generate theoretical insights. By working closely with professionals, partners and end users, the research outcomes become relevant and practical in real-world contexts, enhancing practical impact and knowledge exchange. This integrated approach fosters practical solutions, reflective exploration, and theoretical advancements in the interaction design field.

Pragmatist thinkers, such as John Dewey, emphasise experiential learning ('learning by doing') for knowledge acquisition (Dixon, 2020). However, many interaction design research methods today are empirical, focusing on user-centred design, participatory design and more (Kaptelinin & Nardi, 2009). Weick (1989) suggests a different view, viewing theory construction as a sensemaking process that acknowledges the loose connection between concepts and observables, open systems, and the influence of prior sensemaking on current theories. He also highlights the importance of handling interruptions in design complexity (Weick, 2004). Stolterman and Wiberg (2010) propose a concept-driven approach in interaction design research, aiming to manifest theoretical concepts in designs. Using a case study approach, I will discuss how hands-on design and artefact development play a role in theorising in my research.

In my research, I engaged in practical design activities, creating prototypes for AR concepts in field research at sea as part of practice-led design research. I experimented with various methods, producing valuable insights. I adopted a reflective approach, documenting observations, challenges, and insights. Analysing these, I generated theoretical knowledge to understand design principles and methodologies for AR in ship bridges more broadly.

## 3.2 RESEARCH METHODOLOGY: CASE STUDIES

Pragmatism emphasises practicality, usefulness and real-world application of ideas and concepts (Dixon, 2020). This way, case studies can be considered a pragmatic methodology. Yin (2013) defines a case study as 'an empirical inquiry that investigates a contemporary phenomenon within the real-life context' (p. 16). He further suggests that this method or methodology is especially relevant when the boundaries between a case study and its surrounding context are less distinct. According to Denzin and Lincoln (2011), case studies are characterised by four key elements, which I have categorised as follows:

**Boundaries**
Choosing to conduct a case study is about deciding what will be studied rather than selecting a specific methodology, as the chosen unit can be examined using various approaches, such as qualitative or quantitative methods, analytical or hermeneutical approaches or a combination of methods. The essential criterion for categorising a study as a case study lies in the delimitation of the unit's boundaries, regardless of the specific methods employed.

**Intensiveness**
Due to its delimited context, case studies encompass an emphasis on detail, richness, depth, completeness, and variance within the unit of study.

**Temporality**
Case studies emphasise the significance of developmental factors, indicating that a case usually undergoes a temporal evolution characterised by a sequence of interconnected events that occur in specific temporal and spatial contexts, forming a coherent whole when observed collectively.

**Contextuality**
Case studies concentrate on the relation to contextual aspects of the environment. The process of defining the boundaries for the individual unit of study determines what aspects are considered part of the case itself and what elements constitute the contextual backdrop.

In my thesis, I define exploring design for AR on ship bridges as an explorative case study for addressing my overall research questions. By choosing this case study, I determined the *boundaries* of my investigation, focusing on the design aspects of AR in the specific context of a ship's bridge. To further define the boundaries, I examined a specific AR technology, using Microsoft HoloLens as a particular platform, and focused on icebreaker vessels operating in Arctic waters. The case study approach facilitated an *intensive* detailed examination of the chosen unit of study, allowing me to delve into the intricacies, complexities, and variations within this specific design context and with this specific conceptual material to gain a comprehensive understanding. With the case study, I aimed to capture a holistic understanding of how events occur within specific *temporal* and spatial contexts on the ship's bridge and explore these as interrelated and intertwined with the design process. The research acknowledges the significance of *contextuality*, established by the boundaries distinguishing what count as the case and what is outside of the case – yet in relation to the case.

I would like to emphasise that in comparison to case studies within other fields – such as in social science, where the phenomenon studied is often interpersonal, social or cultural and the physical environment is studied *in relation* to the case – my case study includes the physical environment as *within* the case. Designers tend to have a different view on physical environments as context because they need to have a reflective conversation with the materials of the situation (Schön, 1992). This means that when exploring AR, I considered the physical environment of the ship's bridge and the oceanscape a central part of the conceptual material designed with. However, to define what is *outside* but *in relation to* my case, several aspects exist, and I will define some of them:

- Other existing navigational operations than selected
- Other operational scenarios than constructed
- Other interaction techniques than implemented (such as gesture)

In this study, I define my methodology as *embedded case studies* to identify the overall case study as a collection of lower-level series, or subcases. Embedded case studies focus on specific cases of interest while considering their connections to the larger context, allowing for a research strategy that encompasses multiple subunits in the analysis (Yin, 2013). This approach is particularly valuable when dealing with complex or multifaceted research topics (Scholz & Tietje, 2002).

I identified several embedded case studies within the subprojects undertaken by my team members, making these studies a collaborative effort. I have incorporated these embedded case studies as a methodology in my thesis.

By employing embedded case studies, I was able to explore variations and contrasting cases within the broader research context, evaluating different examples, highlighting similarities, differences, patterns, and exceptions. For instance, each concept development for an AR application can be considered an embedded case study. Our collective goal was to 'think from exemplars' (Kuhn, 1962, cited in Schön, 1984, p. 183) to 'make sense of unique and complex sociotechnical situations by creating a variety of solutions' (p. 203).

My objective was to comprehend the breadth of the overall case study, which encompassed various uncertain elements and interdependencies, by constructing a 'repertoire of exemplars' (p. 274). Employing manageable embedded case studies allowed me to navigate the intricacies of the research topic through a detailed examination of each case while maintaining a comprehensive understanding of the overall context. To simplify the language in this thesis, I use 'case studies' or 'the cases' when referring to the embedded case studies.

## 3.3 RESEARCH SETTING

Delving into practical design work can enhance the process of sensemaking when investigating design complexity (Stolterman & Wiberg, 2010). My research was grounded in practice, and I actively engaged as a member of a design team while conducting this study as both a practicing designer in the OICL team and a research-focused PhD fellow (Fallman, 2008). This approach allowed me as a researcher to adopt a subjective viewpoint and gain profound, implicit insights into the field I was studying, enabling a seamless transition between reflection in and on action (Schön, 1984; Sevaldson, 2010).

The OICL research environment embodies principles of open innovation (Bogers et al., 2019) within a living lab framework (Følstad, 2008; Hawk et al., 2012). This creates a dynamic setting with active participation from industry partners, academic collaborators, and end users. It fosters an iterative, cross-disciplinary research environment characterised by openness and flexibility in incorporating fresh perspectives.

In design practice, it is vital for designers to comprehend not only the systems they design but also the larger context in which they operate (Lurås, 2016b). To study design in the maritime domain, it was essential to acquire practical knowledge through *design-driven field studies*, often referred to as gaining 'sea sense' (Lurås & Nordby, 2015). The insights acquired in the field served as a foundational understanding of the domain and greatly informed the subsequent research conducted in the OICL.

### 3.3.1 My Role in the OICL

My role during the projects was multifaceted, involving different responsibilities as a PhD fellow. I conducted design research for my case studies, engaged as a design researcher on specific project-related tasks, and assumed the role of a lecturer and supervisor for both bachelor and master students as part of my institute duties. Furthermore, I served as a project leader for several field studies conducted on vessels.

Defining my different roles as a PhD fellow, design researcher within the OICL and educator required considerable effort. However, as my project evolved, I noticed that these roles started to intersect and complement one another, resulting in the productive sharing and shaping of valuable insights. Drawing from my background as an interaction designer, I contributed my expertise in designing distributed and multimodal UIs. I also leveraged my previous experience in design systems, usability testing and requirements gathering. During the initial stages of SEDNA, I played a significant role in developing concept sketches and frameworks.

In addition to design work, I was extensively involved in planning and analysing field research. I articulated the research outcomes through exemplars, conceptual models, and methods. I saw my teaching responsibilities as an intriguing opportunity to apply my research perspectives, techniques and explore my research questions within the courses. With this approach, I aimed to enhance students' competence in the methodological approach and the domain relevant to the OICL. Moreover, it provided an excellent means for gathering empirical data from student experiments and their reflections.

### 3.3.2 Study Participants

The study participants consisted of a diverse range of individuals who played different roles within the context of the OICL and its associated projects. These participants can be categorised into four main groups:

**Internal and External Members of the OICL**
These participants were individuals directly affiliated with the OICL, including researchers, designers, engineers, student assistants and project managers. They had in-depth knowledge of the lab's operations, goals, and ongoing projects. Their involvement was crucial for providing insights into the lab's internal workings and the specific challenges and opportunities associated with its innovation processes.

**Stakeholders in the Industry**
This group of participants consisted of representatives from various industry stakeholders, such as companies, organisations and government agencies involved in the ocean industries. Their expertise and perspectives were valuable for understanding the industry's needs, requirements, and future trends. Their participation helped ensure the research findings and design solutions were relevant and aligned with industry demands.

**Field Research End Users**
To gather user insights and feedback, I engaged with end users who were directly involved in the field research activities related to the

OICL projects. These users could be navigators or ship crew, or individuals with practical experience in the specific domains targeted by the projects. Their input provided a user-centred perspective, enabling me to design solutions that catered to their needs, preferences, and work contexts.

**Students**
As part of my research, I also involved students who were enrolled in a course that I taught. These students were not only valuable contributors to the research process but also served as potential future professionals in the industry. Their involvement allowed them to gain hands-on experience in real-life innovation projects and provided a fresh perspective from the next generation of practitioners.

Participant selection was based on specific criteria related to their relevance and expertise in the respective roles. Recruitment procedures involved reaching out to potential participants through formal invitations, personal contacts, and collaboration agreements. Ethical considerations were considered by obtaining informed consent from participants, ensuring confidentiality and privacy, and adhering to any relevant ethical guidelines or protocols.

## 3.4 RESEARCH DATA COLLECTION: A METHODOLOGICAL BRICOLAGE

In several of my publications, I have defined my methodological approach as a mixed methods approach. Since such an approach typically refers to a mix of qualitative and quantitative methods (Tashakkori & Creswell, 2007), I have, for this thesis, chosen to use the term *methodological bricolage* of methods as a more proper description (Yee & Bremner, 2011), which can represent pragmatism in practice (Honeychurch, 2023). In research, the term ‘bricoleur’ metaphorically describes someone who is resourceful and flexible, utilising available tools and materials to achieve a task. I draw inspiration from Claude Levi-Strauss’s concept of bricolage, which explores the fundamental structures influencing human meaning-making (M. Rogers, 2012). Denzin and Lincoln’s (2011) articulation of bricolage within a methodological context expanded the understanding of this concept in social research, offering new dimensions of rigour and complexity. Bricolage encompasses pragmatic, strategic, and self-reflexive practices, involving the use of mixed methods and multiple perspectives (Grossberg et al., 1991). It recognises that different methods carry ontological and epistemological implications, allowing researchers to compare and contrast diverse viewpoints.

In design research, bricolage grants the flexibility to employ established strategies while creating new tools and techniques to address complex questions (Yee & Bremner, 2011). Methodological bricolage emphasises the creative and flexible use of various theoretical and methodological approaches, drawing on a wide range of sources and perspectives to gain a comprehensive understanding of the research topic (Pratt et al., 2022). Further, it encourages researchers to integrate different tools and frameworks to enhance the quality and depth of their investigations. Methodological bricolage is a common characteristic in doctoral approaches for practice-based design research, and the adoption is considered necessary in design research due to the indeterminate nature of design (Yee & Bremner, 2011).

During my PhD research, the specific context of my field formed the utilisation of bricolage. Hence, I adopted a pragmatic stance that involved adapting and further developed existing research methods to suit the premises and possibilities of my research situation. The arrangement of these methods conducted as research activities within the PhD period is depicted in Figure 11.

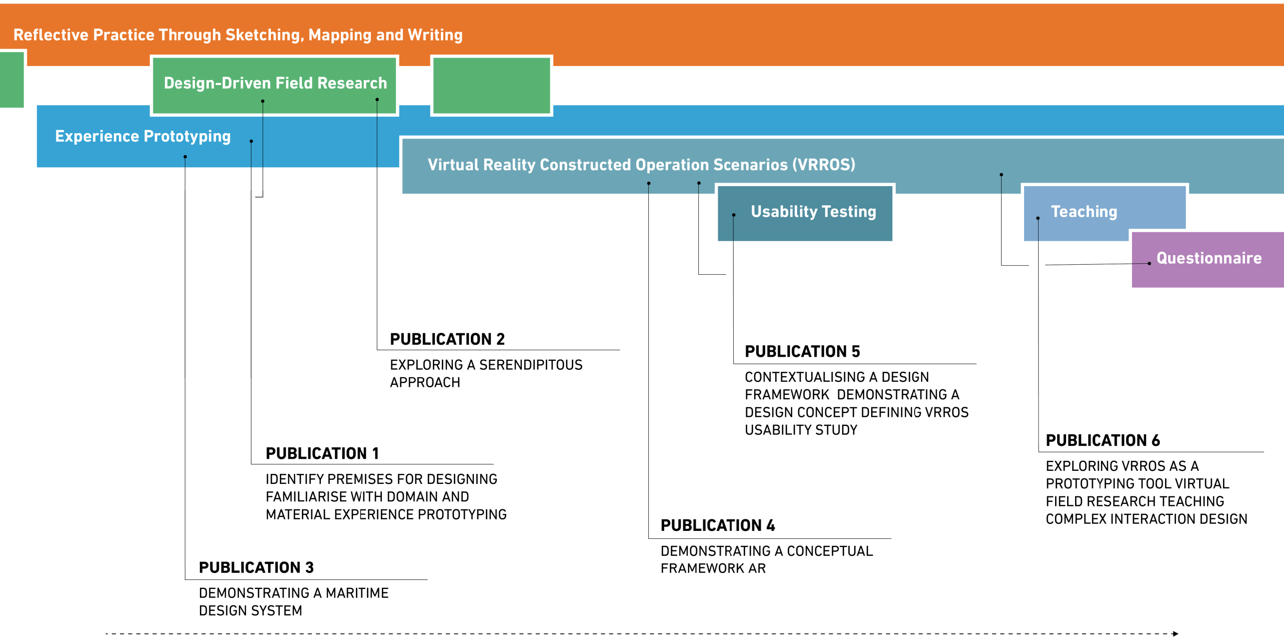



**Figure 21:** The Methodological Bricolage of the PhD.

In the following, I elucidate these approaches and their interrelationships.

**Reflective Practice Through Sketching, Mapping and Writing**
In my research, sketching, mapping, and noting were activities I used to both reflect on and in action (Schön, 1984). They were both planned and spontaneously initiated to serve various purposes individually and as a team effort – for example, for capturing ideas or information for later use, communicating something to or with others, structuring insights, concretising abstract ideas into shapes and definitions, and generalising concrete data into conceptual frameworks (Figure 12). Yin (2013) suggests data visualisation is useful to identify patterns, gain insights and develop concepts in case studies. I found sketching was a tool often available in the design situation, which can thus be termed *a situated strategy* (Gedenryd, 1998). This way can often be experienced as an extension of designers' thinking (Leblanc, 2015). The iterative process of problem-finding and problem-solving required the team to reflect through a conversation with the materials of the situation (Schön, 1992), such as through sketching, mapping, and noting. Hence, I argue it can be difficult to distinguish data creation from data analysis in design.

**Literature Review**
Literature review is a critical and comprehensive summery and analysis of existing research and scholarly publication on a specific topic or research question (Luck, 2014). Although not directly used as a method for data collection in the papers, it served as the research foundation by providing theoretical and contextual background for my work, informing my research questions, and guiding my data collection and analysis (e.g. serendipity research review in Publication 2).

**Design-Driven Field Research**
Design-driven field research, defined by Lurås and Nordby (2015), is described in detail in Publications 1 and 2 (Figure 13). The method included participatory observation (DeWalt & DeWalt, 2011), behavioural mapping on the bridge (Hanington & Martin, 2012), user environment documentation (Beyer & Holtzblatt, 1997), paper prototyping (Snyder, 2003), cocreation (Sanders & Stappers, 2008), eye tracking (Hareide & Ostnes, 2017a), usability testing (J. Rubin et al., 2008), the development of design concepts (Hanington & Martin, 2012) and the collection of visual data as prototyping material.


**Figure 32:** Reflective practice through sketching, mapping, and writing captured during workshops with team members. (Photos: OICL)


**Figure 43:** Design-driven field research on board *KV Svalbard* in the Arctic (Photos: OICL)


**Figure 54:** Experience prototyping by utilisation of the virtual reality-reconstructed operation scenarios in the lab. (Photo: Oever, F.)

**Experience Prototyping**
Experience prototyping refers to the use of various representations, in any medium, to understand, explore or communicate what it would be like to engage with a product, space or system being designed (Buchenau & Suri, 2000). I use this a collective term for what is defined as *concept sketches* (Publication 1), *concepts* (2 and 6), *paper prototypes* (2), *prototypes* (1, 4, 5 and 6) and *design proposals* (3, 5 and 6). In my research, it has involved creating visual and/or interactive prototypes that allow other researchers, designers, partners, and users to actively experience and engage with the design rather than passively observing it (Figure 14). This approach recognises the dynamic, subjective nature of experience and aims to create a shared understanding among the design team, end users and stakeholders by providing a foundation for a common point of view and is valuable in designing complex and dynamic interactions.

**VRROS**
VRROS (Aylward et al., 2021b) are described as a setup and method in Publications 5 and 6. Although VRROS can be used as a tool for training and research, it can also be considered a method when it is part of the systematic approach of experience prototyping (therefore illustrated as a submethod in Figure 11). In my research, VRROS have been used to facilitate several existing design methods like experience prototyping in Publication 4–6, different forms of collaboration and cocreation in Publication 4–6, expert evaluation (following the definition by Roesler & Woods, 2007) in Publication 3–5, user testing (following the definition by Fan et al., 2020) in Publication 5, and teaching in Publication 6.

**Teaching as a Combination of Empirical Study and Research into Design**
Collecting data from research-based teaching is described in detail in Publication 6. In the course, the students explored the different approaches of using VRROS as a design method for experience prototyping and familiarisation with contexts (termed *virtual fieldwork*). This approach encompasses elements of both *empirical study* (Patten & Galvan, 2019), by collecting and analysing data from the students' design exploration resulting in experience prototypes, and *research into design*, by using their projects results and reflections to inform and improve our design teaching and design practices.

**Questionnaire**

We used a questionnaire (Krosnick, 2018) as a structured set of open-ended questions replied to in written free format to collect data from the student group in the course described in Publication 6.

## 3.5 ANALYSIS AND SYNTHESIS IN THE CASE STUDIES: A TEAM EFFORT

Analysis and synthesis are critical components of design (Koskinen, 2014), and documenting them as part of the design research process is key in showcasing its rigour (Stappers & Giaccardi, 2017; Zimmerman et al., 2010). *Analysis* involves the systematic examination of data, design artefacts and observations to uncover patterns, relationships, and insights (Edelson, 2002). This process often begins with the deconstruction of complex design situations into their constituent parts, enabling a deeper understanding of the problem at hand. However, analysis is the least developed aspect of the case study methodology (Yin, 2013). Within interaction design, the approach for data synthesis and analysis is often tailored to the specific research context and objectives (Stolterman, 2008). Hence, there is no single, all-encompassing model that can be applied to synthesise data in projects of real-world design complexity because it has an unclear scope and is influenced by a wide variety of interconnected and interdependent subsystems and impact variables. Thus, the analysis of the case studies needed to be action-oriented since they are theoretically motivated but also typically result from a sincere desire for improvement (Scholz & Tietje, 2002). Conversely, *synthesis* is the process of reassembling these deconstructed elements into coherent and innovative design solutions (Claisse et al., 2019). It involves combining insights, hypotheses, and creative ideas to generate new concepts, frameworks, or design proposals.

Throughout my PhD research, I worked with analysis and synthesis collaboratively in the OICL team. We employed a rigorous approach to both. Analysis allowed us to extract valuable knowledge from the data we collected, while synthesis enabled us to create innovative design solutions. I view these processes as iterative, adaptive, and responsive to the evolving nature of design complexity. Ultimately, I suggest that the dynamic interplay between analysis and synthesis is what drives progress in design research, facilitating an understanding of complex design problems and the development of practical and meaningful solutions.

In the context of design research, the emergence of *design hypotheses* (e.g. defined by Bang et al., 2012; Koskinen, 2014) is closely intertwined with the iterative processes of analysis and synthesis. As we engaged in the examination and deconstruction of complex design challenges in the case studies during the analysis phase, we often encountered indeterminate situations – which can be considered points of tension where our initial comprehension fell short, demanding a deeper understanding (Dalsgaard, 2014). Analysis involved breaking down these complex situations into their constituent components, identifying patterns, comparing data, triangulating methods (Denzin & Lincoln, 2011) and scrutinising the various elements that contributed to the challenge at hand. Throughout this process, akin to *theoretical coding* (Glaser & Strauss, 1967), we strived to discern underlying relationships and uncover potential pathways for addressing different aspects of design complexity in the case studies by developing concepts and categories.

As we moved into the synthesis phase, we transitioned from deconstruction to reconstruction. Synthesis worked as a creative act of organising and clarifying the concepts and categories derived from the analysis through *conceptual mapping* (Ligita et al., 2022). It was the phase in which we sought to transform the indeterminate into the determinate (Dewey, 1938b), striving to convert the fragmented elements of the initial situation into a unified whole. Drawing flexibly upon the Glaserian approach to grounded theory (Glaser, 1998) previously used in case studies (Bass et al., 2018), we employed several synthesis methods to develop theoretical frameworks and conceptualisations.

Design hypotheses began to surface organically as we engaged in synthesis. These hypotheses were conceptualisations or ideas formed in response to the complex challenges identified during analysis. They represented our early attempts to address and resolve the issues at hand, providing a structured approach to navigate the indeterminacy. These conceptualisations took various forms, often manifesting as sketches, experience prototypes or conceptual frameworks.

Crucially, these design hypotheses were not static. They were subject to refinement, adaptation and, sometimes, outright revision as we continued to test them through practical applications. For example, the conceptual models in Publication 1 were substantially altered in Publication 4 due to iteratively applying and generalising insights. As we implemented these hypotheses in real-world systems (see OB design system in Publications 3 and 4), virtual scenarios (see VRROS in Publication 5 and 6) and application proposals (Icebreaker Assistance in Publication 5), we gained valuable insights into their effectiveness. Some evolved into refined design proposals, while others highlighted the need for new adapted hypotheses, informed by both past attempts and newly acquired information.

In essence, the design hypotheses functioned as the bridge that connected the analytical understanding of design complexity with the creative and practical solutions developed through synthesis. They represented our initial attempts to bring order and determinacy to inherently complex situations while guiding our ongoing journey through the iterative processes of design inquiry.

## 3.6 KNOWLEDGE INTEGRATION

Scholz and Tietje (2002) propose a three-level framework for organising and structuring analysis for embedded case studies, encompassing *understanding, conceptualising,* and *explaining*. To explain the architecture of knowledge integration from the case studies to my PhD's overall theoretical aim, I propose an adapted model (Figure 15) based on both Scholz and Tietje (2002, p. 30).

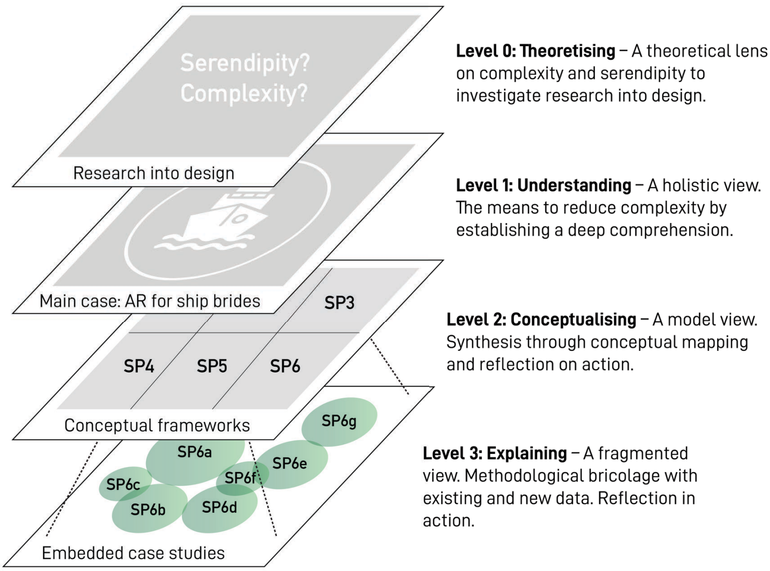



**Figure 15:** The Architecture of Knowledge Integration Adapted to This Research from Scholz and Tietje (2002, p. 30).

In this adapted model, I interpret the epistemic levels of my case studies in relation to this framework as follows:

**Level 0: Theorising from Case Studies**
I have introduced a Level 0 in the model, which serves as a meta level representing my individual knowledge integration within this thesis. This level was not originally part of the model but has been included to reflect the theoretical perspective of my research questions representing research into design. It plays an essential role in my individual knowledge integration from the case studies, specifically in addressing design complexity and the cultivation of serendipity through research into design.

**Level 1: Understanding – A Holistic Comprehension**
Level 1 signifies the main case study that align with the research projects concentrating on the exploration of premises and possibilities within interaction design, specifically involving novel interaction materials on ship bridges. At this level, a collective effort was made to integrate knowledge as we used research by design to delve deeply into the distinctive characteristics and context, relying on mental images and an intuitive understanding.

**Level 2: Conceptualising – Principal Frameworks**
The second level involves mental models aimed at conceptualising the real world by synthesising the data and results from the third level. At this stage, knowledge integration methods acted as delivery systems for the synthesis, contributing to the establishment of a stronger foundation for case comprehension. Collaborative synthesising across the intersecting case studies played a pivotal role at this level.

**Level 3: Explaining – Practical Exemplars, Data and Results from the Case Studies**
Third-level information includes distributed findings from the subcases, where distinct aspects, questions or application areas were investigated. This level involved case-specific information collected from interviews, participatory observations, expert opinions, and other sources or generated through prototypes, cocreation or other generative design activities and data and insights derived from the existing scientific knowledge base.

My primary focus in my doctoral studies was on research by design represented by Levels 1–3 (Figure 15). My efforts primarily involved data analysis aligned with the case study research questions (Publications 1, 3–

6). Level 0, representing the research questions, utilised the case studies as data for research into design. As a result, this form of analysis required additional frameworks and methods to theorise the knowledge.

## 3.7 THEORISING

In Section 2.5, I defined and established boundaries for design complexity and serendipity. My objective was to develop a *theoretical lens* (Niederman & March, 2019) that would provide clarity and distinction for these concepts, especially in the context of pragmatic design. This framework became an essential tool in my analysis of the embedded case studies.

Regarding design complexity, the theoretical lens enabled me to refine and expand 'WHAT' and 'HOW' as dimensions of complexity, tailoring them to the specific field of interaction design. This adaptation involved a meticulous examination of how these dimensions manifested within the actual case studies. Through this analysis, I identified case-specific subconcepts intricately linked to design complexity, firmly situated within these refined dimensions.

Additionally, as I addressed the cultivation of serendipity, the theoretical lens proved invaluable. It facilitated the process of applying codes to uncover potential underlying mechanisms, personal capabilities, and deliberate strategies within the data. Subsequently, I organised these elements into distinct categories by interpreting the data and drawing connections between observed patterns and the foundational theoretical constructs. This comprehensive exploration led to the identification of several pivotal concepts that underpin the cultivation of design within the design process. Selection of these concepts was driven by the goal of encompassing the most fundamental aspects of design practice.

It is important to underscore that my research, conducted as part of the OICL research group, involved an iterative process of analysis influenced by informal discussions with the other team members. These discussions were integral to refining coding patterns and conceptual mapping throughout the analysis. Moreover, to formally verify and refine my analysis, I organised three structured peer-review sessions involving team members who had been actively engaged in the research projects over the course of my study. The primary aim of these workshops was to critically evaluate the analysis and synthesis of my research. Given that my research questions were centred on the design practices observed in the case studies, it was imperative to determine their relevance and significance. Additionally, these sessions served to counteract potential biases and narrow perspectives stemming from my professional competence and established practices.

During the sessions, participants were presented with statements summarising key findings derived from the case studies, representing various subconcepts. I encouraged them to collectively reflect on the interpretation of these findings, considering their implications and relevance within the coding structure. We also delved into specific examples from the case studies to provide context and align the knowledge generalisation. I shared proposed theoretical models designed to support the framework of concepts and subconcepts. Participants were tasked with evaluating the composition of these models in relation to the findings and assessing their effectiveness in representing the research outcomes.

In the final phase, I consolidated and harmonised the concepts and findings from the initial two phases. The peer review sessions yielded numerous fresh examples, perspectives, nuances, and corrections, all of which were integrated into my analysis and synthesis. This was achieved through a thorough revision and a partial restructuring of the research outcomes. The synthesis process, performed individually, entailed iterative comparisons and refinements of the materials obtained from the first two phases. The primary aim was to articulate cohesive concepts that could bridge the six publications, shedding new light on the cultivation of serendipity within design practice and providing a novel perspective on how to comprehend design complexity in this context.

## 3.8 ETHICAL CONSIDERATIONS

Ethical considerations played a pivotal role throughout the research process. The research protocol underwent a thorough review and received approval from the university's ethics committee – Sikt (2023), formerly the Norwegian Center for Research Data. Nonetheless, I encountered several ethical challenges in my interactions with various stakeholders.

First, during the design-driven field research, ensuring the privacy and informed consent of the crew members, who both actively and passively participated onboard, was of utmost importance. The research team conducted an informational meeting and obtained written consent. However, it also required a degree of social acumen and SA to discern who wished to actively engage in participatory observation. This depended on various factors, such as their current roles, operations, conditions, collaborators, time of day, mood, and the data collection method. In this context, practicing reflexivity (Salzman, 2002) became essential. Reflexivity involved acknowledging and critically examining my own influence on the research process and its outcomes.

Second, when collecting data in the teaching module, I took measures to protect the privacy of the participating students. Informed consent was secured from all participants, and their anonymity and privacy were safeguarded throughout data collection, analysis, and reporting. Third, I also considered the privacy of my team members within the OICL group involved in the research projects. In the analysis of the case studies, conducted with the aim of researching *for* design, I explored the cultivation of serendipity undertaken in the team constituting a different perspective than in the primary analysis. Privacy was ensured by involving the participants in the analysis and synthesis process, specifically through peer review sessions, and allowing them to review the results of the process.

Lastly, it is essential to highlight that ethical considerations should be formulated as requirements when designing for a high-risk domain and a technology with uncertain and undefined design precedents and guidelines. Further details on this topic are provided in Section 4.2.

# 4 RESULTS PART I: CONCEPTUALISING DESIGN COMPLEXITY

In this chapter, I will present the first part of my results. The case studies in Publications 1–6 have illuminated distinct facets relevant to addressing my first subsidiary research question: *What are the fundamental aspects of design complexity that interaction designers need to comprehend and address?* Here, my theoretical framework is employed to dissect design complexity as dimensions that collectively form a complexity landscape. Additionally, I will explore the characteristics of these dimensions and contextualise them based on the case study data.

## 4.1 DEFINING THE 'WHAT' AND 'HOW' IN DESIGN COMPLEXITY

The research presented in the publications were driven by abductive reasoning (Peirce, 1958). This involved melding knowledge, empirical data, concepts, and ideas into abstract prototypes for testing and discussion concerning their practical applicability, academic relevance and experimental feasibility. From a general perspective, this can be understood as relying on the best guess. This abductive reasoning approach for design, (Figure 7 in Section 2.3.6), serves as a lens to comprehend how designers engage with formal logic of the terms 'WHAT' (the object/service/system), 'HOW' (the working principle) and 'ASPIRED VALUE' when grappling with complexity in their work (Dorst, 2011, 2015b).

In my case studies, the 'ASPIRED VALUE' was to explore how navigation systems for navigators on ship bridges can be designed to enhance SA, efficiency and UX, whereas the 'WHAT' and 'HOW' were variables of rather unknown or uncertain knowledge. However, the 'WHAT' was uncertain due to several reasons:

- A ship's bridge is a fundamentally complex workplace to design for; it consists of many interrelated systems, representing advanced operations, and is characterised by demanding and changing conditions.
- A ship's bridge is an unfamiliar and inaccessible context for designers to understand and work in.
- Efficiency, UX and especially SA are demanding qualities to evaluate in high-risk domains.

- AR lacks design precedents and guidelines.

The 'HOW' was likewise uncertain throughout the case studies due to

- The lack of design precedents and guidelines for designing AR UIs for ship bridges and
- Rapid technological development in both hardware and software related to AR.

The lacking content of the 'WHAT' and 'HOW' is intertwined, meaning that they affect each other, and both dimensions must be determined simultaneously. This way, abduction-2 can be differentiated from traditional problem-solving (Dorst, 2011). In the following, I define a conceptualisation of 'WHAT' and 'HOW' in design and contextualise this in the case studies.

## 4.2 REQUIREMENTS FOR DESIGNING

I propose that 'WHAT' may represent what I define as *requirements for designing* in a project. This way, the 'WHAT' represents something different from what Dorst (2015b) refers to as 'the elements'. Requirements for designing can be well defined – making a task straight forward to solve or ambiguously defined, thereby requiring the designer to research, analyse and experiment to propose a set of requirements. In analysing the case studies, I found that the requirements were often competing or even contradictive, making the balancing and negotiation of the requirements for designing challenging in the design process to reach the aspired value. In the publications, we address the high uncertainty of the requirements for designing through conducting design-driven field research (1 and 2) and design experimentation through prototyping (1–6), by establishing design systems and frameworks (3 and 4), with user testing (5) and by virtual techniques to familiarise, prototype and evaluate (6).

Based on analysis of our findings from an overall level, I have defined a selection of design requirements representing the domain of interaction design (Table 4).

| Concept | Description |
|---|---|
| Requirements for Designing | Functionality |
| | Interaction |
| | Usability |
| | Form Factor and Ergonomics |
| | Lighting and Environment |
| | Display Quality |
| | Technology Platform |
| | Regulations and Law |
| | Environmental and Ethical Considerations |
| | Cost and Time |
| | Stakeholders |

Table 4: List of Requirements for Designing

In the following, I will describe these specifically contextualised in the case studies of the design of AR for ship bridges.

### Functionality

Functional requirements encompass specific functionalities for the user to achieve their goals in interacting with the systems designed. Since ship bridge operations are complex and characterised by changing conditions, achieving an overview of the functional requirements is considered challenging (Lurås et al., 2015). The design-driven field research, described in Publications 1 and 2, resulted in important insights into preferences, behaviours, and pain points. Through extensive task analysis, we developed VRROS (Publications 4–6) that provided a detailed narrative of how the users would engage with the design and helped define specific functionalities. We prioritised the identified functionalities based on their importance and impact on our aspired value. The more complex the functionalities were, the greater the need for decomposition into manageable components (Publication 5). We compiled the identified functionalities into several requirement documents and systems that were iteratively updated, such as the OB design system (Publications 2, 4 and 5).

### Interaction

Interaction requirements consist of both *aesthetic requirements* involving the UIs' layout and visual consistency by defining desired look, style and visual appeal through specified colour schemes, typography, graphical elements, branding guidelines or overall design systems, such as the OB design system visualised in Figure 16 (Publications 3, 4 and 5). *Control and navigation requirements* within the system UIs represents the definition of means and modes of interaction by defining input sources and information management. This form of requirements aims to create a seamless and intuitive UX. We approached the lack of interaction requirements for AR design by exploring the limitations and possibilities for the application of UI components, patterns, and principles. Due to the complexity of the domain and the uncertainty of novel technology application, it was of great importance to experiment and evaluate this *in context* – either in the field or through VRROS and through a user-centred approach, where users, domain experts and vendors were closely involved in defining, codesigning and evaluating.


**Figure 16:** Interaction requirements exemplified in the OpenBridge design system. (Photo: OICL).

### Usability

Usability requirements represent the UX and the ease of use. At the time the case studies were employed, there existed no formal usability requirements regarding design of UIs for maritime AR. We addressed important factors for general usability, such as consistency in UI design, usefulness according to functional requirements, appearance, placement, and improvement of SA. Since it is difficult to evaluate usability requirements for AR in a safety-critical context during real operations, we experienced high uncertainty according to these requirements. However, through the user-centred and stakeholder-oriented research activity, we used abductive reasoning to assess the formulation of usability requirements. In Publication 5, we describe how we conducted usability tests of the 'Icebreaker Assistance' app through the VRROS by investigating how navigators experienced the app to enhance SA.

### Form Factor and Ergonomics

Form factor and ergonomic requirements ensure that UIs are comfortable, efficient, and user-friendly to interact with. The HMD AR headset, Microsoft HoloLens, has a unique form factor and ergonomic design to provide an immersive UX with the context (Zeller et al., 2019). Since case studies aimed to enhance SA, safety and efficiency during safety-critical operations, form factor and ergonomic requirements were key concerns in developing frameworks for AR. In the case studies, we have particularly been concerned with exploring the requirements for information placements in the oceanscape and on the ship's bridge, button placements, appearances, and interaction modes of AR. Early design proposals, such as the navigational information overlay on the ocean surface (Figure 7 in Publication 1), can in hindsight demonstrate a steep learning curve in exploring the difficult balance between cognitive support and visual ergonomics in designing for navigation. However, cultivating serendipity entails exploring innovative placements, appearances, and interaction modes for AR elements to discover the premises and possibilities. The incorporation of the users' environment as a potential screen for augmentation heightened the importance of requirements to a new level.

### Lighting and Environment

Lighting and environmental requirements define designing for a range of lighting conditions and in different types of environments. The field research indicated these are central requirements when designing for AR to be used on a ship's bridge, as this requires careful consideration of the colour, contrast, and brightness of digital information and how it will appear in different lighting conditions. Results from the field research revealed an unexpected effect of the extreme light contrast between looking at instruments inside the bridge and outside on the oceanscape during daytime, especially in ice-filled waters. We suggested that an important requirement for designing for AR UIs is to design daylight palettes (Publication 1). There was a further development into four palettes ('bright', 'day', 'dusk' and 'night') (Publication 3) for AR (4) and in a contextualised form (5 and 6).

**Display Quality**

Display quality requirements concern design for specific hardware and display technology. We found that this requires understanding the limitations of the display technology, such as resolution, colour gamut and refresh rate, and designing interfaces that are usable and accessible under these constraints (Publications 1 and 5). In the field research using Microsoft HoloLens, we experienced several issues regarding display quality – some worsened or triggered by the contextual conditions, such as movement and light. However, while some issues are constant, others can be considered results of immature technology and can be overridden by, for example, self-made hacks, such as described by my coresearcher Jon Olav Eikenes (2019) in 'How to Create Your Own HoloLens Sun screen'.

**Technology (Material) Platform**

The technology platform specifies requirements for the technology to be used in the system's construction, taking into account subfactors such as *performance requirements* defining expected performance levels in the product (e.g. response time, processing speed and system reliability); *security and privacy requirements*, representing user data protection, maintaining confidentiality and preventing unauthorised access; and *compatibility requirements*, representing the system's compatibility with other systems, software and hardware. In the case studies, the combability requirements represented the distribution of the system across multiple integrated instruments and subsystems on the ship's bridge.

The technology platform requirements may address development constraints, such as reliability on sufficient spatial mapping, battery life, display and field of view, processing power and performance and input methods. During the field studies, we experienced several challenges related to development constraints, such as insufficient spatial mapping on the ship's bridge due to strong daylight. However, the design requirements for AR headsets are rapidly changing in pace with the technological development contributing to the uncertainty of which constraints are pertinent and which will be resolved in the next generation of AR equipment. Therefore, in the case studies, we relied on the best guess of what would be technologically feasible.

**Regulations and Law**
Regulatory and legal requirements represent industry-specific guidelines according to safety, law, and usability. In our case studies, we adhered to the specifications outlined in the International Electrotechnical Commission (2021) standard 62288:2021. This standard defines the general requirements, testing methods and necessary test results for the presentation of navigation-related information on shipborne navigational displays. It aligns with IMO regulations, particularly IMO (2021) Resolution MSC.191(79).

However, these conventions do not specifically address AR, leading to a lack of consensus on how to apply the AR design requirements. In the research focused on the screen-based development of the OB design system, we utilised the international standard WCAG 2.1, published by the Web Accessibility Initiative (2018), as a guiding framework. However, these guidelines are not currently considered requirements in the maritime sector. When adapting UIs to AR, as explored in Publications 3 and 4, we encountered limitations with the applicability of WCAG. One of the contributing factors was the altered criteria for contrast and visibility in a ship bridge environment, especially under extreme daylight conditions, as detailed in Publication 1.

**Environmental and Ethical Considerations**
These requirements play a crucial role in design projects, as they focus on developing *inclusive and humane working environments* for the users. Since working in a high-risk domain presents challenging conditions, the aim is to design tools and systems that not only increase the users' experience of safety and well-being but also improve their capacity to perform better while operating the ship's bridge. Therefore, we had a focus on enhancing SA through *responsible innovation*. When applying new technology to a complex workplace with a lack of design precedents and guidelines, considering potential risks and unintended

consequences was key. This gap has driven my motivation for the research on establishing responsible requirements.

*Efficiency* in the implementation and maintenance of designed systems can impact the environment. This was a core consideration in the development of the OB design system (Publications 3 and 4), as it was designed to be responsively distributed across multiple instruments, systems, and vendors. The OB design system also supports *inclusivity* and *accessibility* for users through design consistency, as defined in Publication 2.

### Cost and Time

Cost and time requirements represent important constraints in a design or research project to ensure efficient resource allocation, budget management and timely delivery of the project. The research projects which the case studies are based on have had defined scopes, objectives, budget, deadlines, resource allocation and risk management. Vendors and research partners included have been evaluated and included based on their ability to deliver and manage timelines. By establishing unformal and fluent communication channels, such as through the cloud-based collaborative software Slack, we were able to cooperate in efficient ways. The iterative, incremental, and coevolving process employed throughout the case studies accommodated change management, allowing serendipitous insights to shape resource allocation and timeline adjustments. This is further detailed in Chapter 5 in Concept #2 The Design of the Process and #3 Serendipitous Team Dynamics.

### Stakeholders

Stakeholder requirements refer to the needs, expectations and preferences of individuals or groups who have vested interests in or influence on the design outcome. These requirements may represent some of the ones mentioned above but may also represent specific claims. In Publications 1, 2 and 5, we describe analysis and collection requirements from navigators representing the stakeholder group *end users* in the case studies. In Publications 3 and 4, we describe the interests and needs of the stakeholder group *system vendors* for maritime systems and instruments. In Publication 6, I describe *students* as a stakeholder group for testing elements of the serendipitous approach. Cultivating serendipity within stakeholder requirements involved actively seeking insights that aligned with stakeholders' interests while being open to unanticipated viewpoints or preferences.

In this section, I have defined a comprehensive set of requirements for designing in the context of interaction design, particularly in the domain of AR for ship bridges. These requirements encompass diverse aspects and require adaptation to other interaction design contexts. The cultivation of serendipity within these requirements involves maintaining a balance between established guidelines and innovative exploration while considering the perspectives and needs of stakeholders.

## 4.3 FORMGIVING

The term 'HOW' can encompass the process of *formgiving* in a project, differing slightly from Dorst's (2011) 'working principle'. According to Bjarke Ingels Group (2020) architects, the concept of formgiving, prioritises materials, offering a holistic, context-responsive design method transcending stylistic considerations. Moreover, formgiving is a term used in both industrial design and crafts (Abidin et al., 2008; Anwar et al., 2015). I define formgiving as the process of harmonising the requirements for designing by addressing aesthetic, structural and material considerations to craft an intended UX.

Technologies, treated as materials (whether physical, digital, or virtual), emphasise materials' role in shaping interaction design (Blevis et al., 2006; Wiberg, 2018). Reflective design discourse intertwines with methodologies and material selection, influencing engagement with technology (Schön, 1992). Material methodologies shape technology interaction, extending into interaction design (Wiberg, 2018). In interaction design, formgiving concerns relate closely to the chosen material, including technology. Defining these concerns becomes vital, especially for intangible, dynamic interaction (Löwgren & Stolterman, 2007).

In the publications, I address the high uncertainty of formgiving parallel to the requirements for designing. Based on analysis of our findings from an overall level, I have defined a selection of formgiving aspects representing the domain of interaction design. In the specific context of AR design, additional concerns arise regarding formgiving and interaction design. The complex nature of AR necessitates careful attention to aspects such as interaction gestalt and the translation of interaction attributes into properties of interaction artefacts. By exploring these concerns through case studies and publications, the inherent uncertainty throughout the design process becomes evident.

| Concept | Description |
|---|---|
| Formgiving Concerns | Contextual Integration |
| | Interaction Patterns and Navigation |
| | Responsiveness and Adaptability |
| | Scale and Proportion |
| | Placement and Positioning |
| | Timing and Duration |
| | Dynamic Updates |
| | Transitions and Animations |
| | Ergonomics |
| | Situation Awareness Support |

Table 5: List of Formgiving Concerns

The list of formgiving concerns presented here serves as a foundational starting point for discussion, but it is not intended to be exhaustive (Table 5). Instead, it encourages ongoing exploration and dialogue regarding the critical considerations for formgiving in AR interaction design, which are further outlined below.

### Interaction attributes

Attributes are specific qualities or characteristics that arise from design decisions and directly influence how users perceive and interact with the design. Interaction involves user-artefact interplay, with attributes such as *connectivity, movement* and *orderliness* shaping the experience (Lim et al., 2007). Conveying these attributes in the artefact is crucial for a meaningful UX. For context, I apply the widget display for point of interest (POI) information in the AR app Icebreaker Assistance (Figure 17) (Publication 5) to an adapted model of interaction gestalt (Lim et al., 2007). The model shows one type of interaction attribute – proximity of controlling information (purple) and describes its translation into interactive artefact, artefact properties, UX and UX qualities. For each increment we developed in the case studies, there were numerous attributes that needed to be translated and manifested into properties of the interactive artefact and interpreted into qualities of the UX. For example, the attribute of proximity ranges from precise to proximate and is defined by the properties of the interaction artefact. To evaluate proximity as a quality, it needs to be experienced by the user through the interaction gestalt. As a result, the requirements of designing (WHAT) and formgiving (HOW) are intertwined in addressing aspired value.

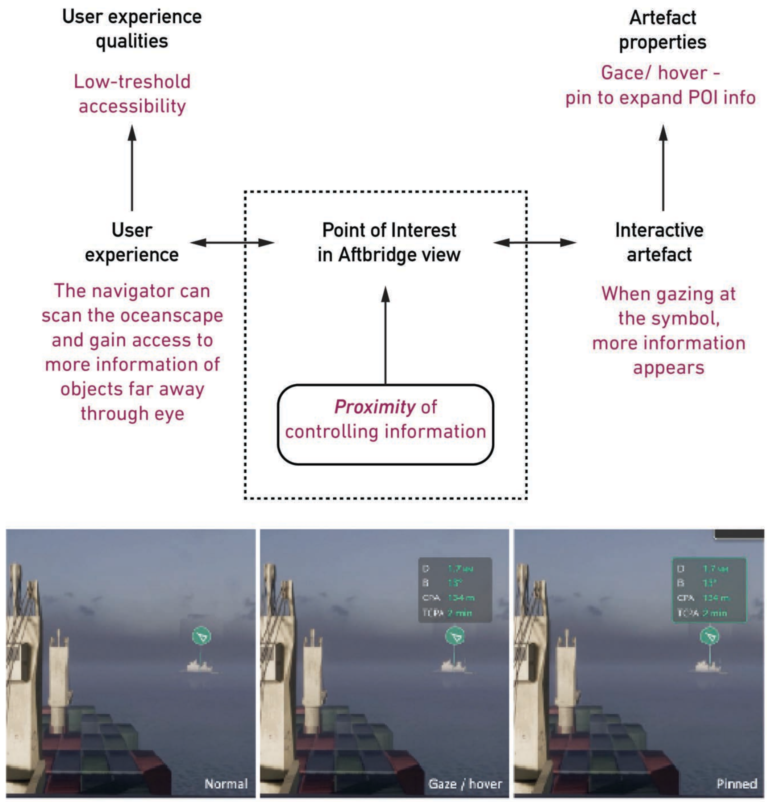



**Figure 17:** Interaction Gestalt Model (Lim et al., 2007) exemplified with point of interest widget in aft bridge view in the 'Icebreaker Assistance' app from Publication 5.

In proposing this model, I wish to highlight the distinction between UX qualities and properties of the interactive artefact, which is not linear, but rather entails a serendipitous potential in both how the attributes are translated into an interactive artefact by the designer and how they are interpreted and approached by the user.

### Contextual Integration

Contextual integration describes the concern with context in which the interactive system will be used and how we can design UIs that seamlessly integrate with the user's environment and workflow. As an example, AR utilises *spatial mapping* to understand the user's physical environment. Design for AR applications should ideally take advantage of this feature by incorporating spatial mapping data to design UI, as this allows holograms to interact with real-world objects and align with the physical environment accurately. However, we found that integrating the dynamic, complex and changing context of a ship's bridge implied high levels of uncertainty for the formgiving. This is due to the inconsistent spatial mapping and constantly changing premises for using the space, as described in Publication 1. To help define the concern of contextual integration, we suggest a model (Publication 4) for information areas and five forms of integrating information in the context – *app display, widget display, AR map, annotation,* and *ocean overlay*, containing various premises for use. By defining certain formats of integration, we could explore the boundaries and possibilities within these to establish 'a best guess'.

### Interaction Patterns and Navigation

These concerns define consistent interaction patterns and navigation structures that users can easily understand and follow by providing clear signifiers, affordances, and feedback to guide user interactions. AR supports various input methods, including gestures, voice commands and gaze tracking. Designing AR applications can therefore provide intuitive and natural interactions by utilising hand gestures, voice commands and eye tracking to enable users to navigate, interact and manipulate holographic elements seamlessly. However, we found that the lack of guidelines and design precedents generally, and on a ship's bridge specifically, made this concern challenging. Our research results indicated that a ship's bridge may set conditional premises for interaction modes; for example, hand gestures can be difficult or impossible in a dynamic environment, especially if the user needs to keep in handrails, or voice commands can be difficult due to noise. Hence, we limited our focus to visual interaction, with an emphasis on displaying information for monitoring rather than extensive control of functions or deep navigation structures through interaction with the AR UIs.

### Responsiveness and Adaptability

These concerns define design for changing needs according to context and user situation by adapting responsively regarding, for example, screen sizes and input methods. For AR, this concern includes designing for distributed and multimodal use. The results of the field studies demonstrated the importance of considering how digital information changes as the user moves around the physical environment. Among several aspects, we addressed responsiveness according to *user movement* and *attention* on the bridge (referred to as *user zones* [Publication 4]), contextualised as UIs with appearance responsive to where the user watches from where they stand (Publication 5).

### Scale and Proportion

The concern of scale and proportion defines the design of AR UIs proportional to the physical environment so that digital information appears in a way that makes sense in the real world. We found that this involves considering the size and scale of digital information relative to the physical environment and, potentially, to the type of situation. Through experimental design and scenario-based prototyping (VRROS), we found that UI components placed in the oceanscape, often fixed to dynamic or static points, lines, regions, or volumes of interest should not necessarily be represented through scale, even though the oceanscape is a huge space, but rather through type (Publication 4). In formgiving POI widgets for the oceanscape, the formgiving focused on giving the navigator a perception of proportion by fixing the vessel data (POI) to the actual position (5).

### Placement and Positioning

These concerns represent the placement of digital information in a way that makes sense in the physical environment. The findings from the field research (Publication 1), design cases (4) and user testing (5) reveal key factors to consider, such as the user's line of sight and perspective and the position of digital information relative to physical objects in the environment. From a ship's bridge, many points, lines, or volumes of interest appear far away and are thus located in the horizon line, while interests appearing closer are located on the ocean surface between the vessel and the horizon line (Figure 18). In the field research, we developed this formgiving concern through discussing and codesigning design ideas with the ship bridge crew (1 and 2) in context and found that information overlaying important areas, such as the ocean surface, was problematic for maintaining SA. Consequently, we developed the *sky band* as an information area in the AR design frameworks that can be designed to contain information above the horizon but connected to the POIs on the ocean surfaces with a thin line (4 and 5).

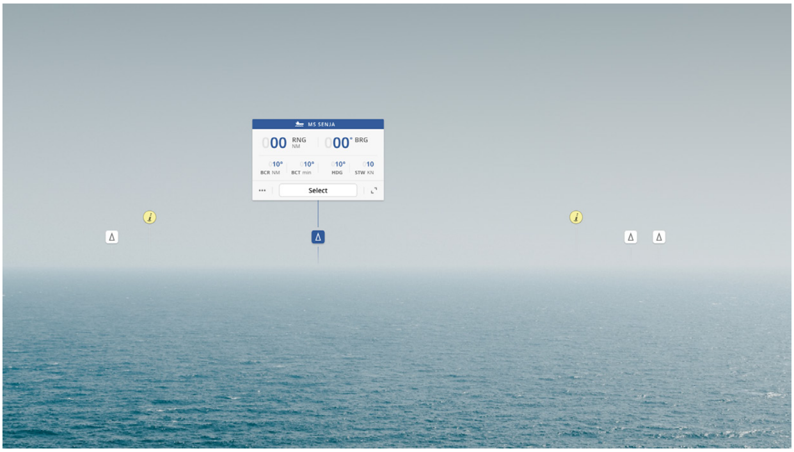



**Figure 18:** Information with placement related to the horizon line. (Photo: OICL)

### Timing and Duration

This concern defines formgiving of the temporal aspects of an AR UI. The results of the user tests in Publication 5 pointed to timing of the right information in the situation as key to improving safety. Further, in the design cases, we found that the persistence of digital information in the physical environment should be designed according to the users' movement (4) – implying it may remain in place as long as it is relevant, even as the user moves around. This involves considering factors such as the duration of the digital information and how it will be updated or removed when it is no longer needed.

### Dynamic Updates

This concern defines the design of AR UI to allow digital information to be updated in real time so that it remains relevant and up to date. Based on the design cases (Publication 4), we suggested considering how digital information will be updated as new information becomes available with the user moving or altering their gaze. Further research should also focus on how the user will be notified of these updates.

### Transitions and Animations

This concern defines the formgiving of AR UIs to have digital information transitioning between *different states* in a smooth and seamless way (Figure 19). We found that that this concern can affect the user's experience of actuality by, for example, changing colour from green to orange to red, according to the risk of collision if the course is not altered on a POI in the oceanscape (Figure 7 in Publication 4), or by indicating speed difference in the arrow between the vessel representations on the information pane (Figure 4 in Publication 4).

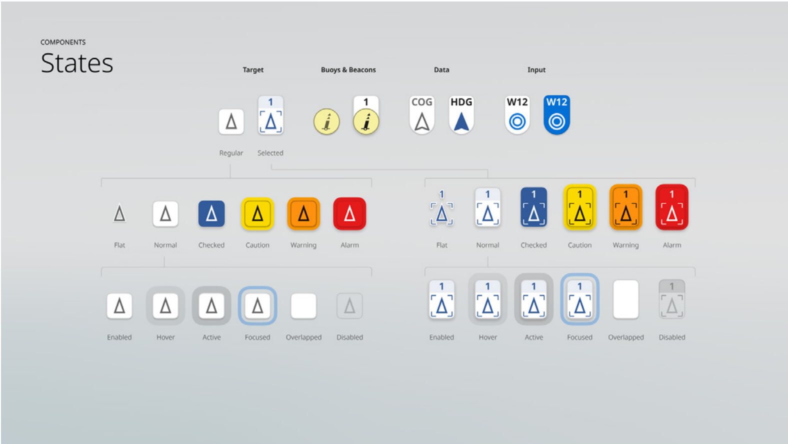



**Figure 19:** Points of interests designed with different states exemplifies the formgiving concern of transitions and animations. (Photo: OICL)

### Ergonomics

Ergonomics defines the concern of formgiving AR UIs to consider factors such as the *user's field of view, eyestrain, comfort during long-duration* use and *movement*. The field research indicated that avoiding placing critical information at the extreme edges of the field of view and providing breaks for users to rest their eyes were important (Publication 1). Further, through participatory observation and explorative equipment testing on the ship bridges, we found that the external movement of the dynamic environment was affecting the users' visual and bodily perceptions of their surroundings, thus heavily affecting the experience of the UIs. Consequently, instead of fixing graphical elements to a body sphere or location-based coordinates, we suggested fixing AR UIs, used on a ship's bridge, to the ship structure to secure ergonomic issues, such as balance and avoidance of nausea. On the other hand, AR UIs in the oceanscape can be fixed to points, lines, regions, or volumes of interest in the physical world.

### SA Support

This concern defines the design of AR UIs to respond to the user's needs, intentions and how the user is performing. Formgiving UIs to support SA need to respond to the three levels of SA: perception, comprehension, and projection of the future status. This affected how we gave form to the information presented in the UIs in relation to all the previously described concerns. In the field research (Publication 1), design cases (Publication 4) and usability study (Publication 5), we found that *reducing information overload* by *prioritising critical information* could be essential for enhancing SA. Further, participants in the user test highlighted the need to turn widgets on/off manually when needed. They further highlighted the ability to maintain a *heads-up position* supported by *spatial awareness* by linking digital information to real information in the oceanscape as likely to improve SA, as exemplified in Publication 5. In addition, the participants advocated for the option of obtaining the most important information while hiding other layers (i.e. a *visual hierarchy*) as key.

This section introduced formgiving concerns in the context of AR interaction design, emphasising their role in harmonising requirements for designing and encompassing aesthetic, structural and material considerations. It discusses the importance of addressing uncertainties in formgiving and the challenges specific to AR design. The various concerns addressed are considered as foundational for further exploration and dialogue in the field of interaction design.

## 4.4 THE INTERTWINEDNESS OF TWO DIMENSIONS OF COMPLEXITY

Through my research, I found the exploration and categorisation of the 'WHAT' and 'HOW' vital for the realm of design complexity – as it allowed us to dissect the reasoning patterns that designers employ, highlighting where the complexity is found: in the requirements for designing or the concerns for formgiving or both. As contextualised with the design of AR for ship bridges, the dimensions can be characterised by a general *low agreement* in what the design requirements are and how they should be balanced, and a general *low certainty* according to guidelines and design precedents in the formgiving concerns. I suggest that they can therefore be characterised as complex according to abductive-2 reasoning (Dorst, 2011), decision-making (Stacey, 1996) and sensemaking (Weick, 2004).

Although I have distinguished the variables 'WHAT' and 'HOW' and categorised them into two separate dimensions, they are often intertwined. The *intertwinedness* of design complexity exists at several levels:

**A Problem That Is Dependent on Another**
This can be exemplified by the understanding of how the integration of new elements of reality (AR) into a user's existing reality is dependent on understanding the context of a ship's bridge as it already is (complex).

**A Problem That Creates a New Problem**
This can be exemplified by a misinterpretation of the existing complex user situation, thereby producing trailing errors in the attempt to accommodate the user needs in the design of new interventions.

**A Problem That Exacerbates Another**
This can be exemplified by a design that fails to adapt to the user environmental conditions exacerbating the problem of maintaining good SA.

Although intertwined, I propose that the definitions of the two dimensions can contribute to a specificity in the understanding of cause and effect in design complexity.

## 4.5 SUMMARY OF THE CHAPTER

In this first results chapter, the overarching theme revolves around understanding and managing design complexity contextualised within the cases of exploring the design of AR on ship bridges. The results highlight the nature of two dimensions: requirements for designing ('WHAT') and formgiving ('HOW'). These intertwined complexities are presented as challenges that designers face, including dependency, problem creation and exacerbation. Overall, the articulation and contextualisation of these dimensions offer valuable insights into the multifaceted nature of design complexity and its implications in the context of AR design for ship bridges.

In the upcoming Chapter 6, I will further explore how designers can navigate design complexity by conceptualising these dimensions within a matrix model. However, before discussing cultivating serendipity within this model, I will present the results in detail in the next chapter.

# 5 RESULTS PART II: CULTIVATING SERENDIPITY IN DESIGN

In this chapter, I will present the second part of the results, focusing on the exploration of serendipity and its deliberate integration into the interaction design process to enrich sensemaking and foster creative outcomes. The chapter addresses the second subsidiary research question: *In what ways can serendipity be deliberately nurtured and integrated into the interaction design process to enhance sensemaking and creative outcomes?* Central to this exploration is the conceptual framework, which defines key aspects and elements essential for this integration. These aspects and elements are drawn from the insights gathered from the case studies, forming a foundation for the ensuing presentation and discussion. The chapter culminates in the encapsulation of these research findings within four distinct, yet interconnected, concepts highlighting the intricate interplay between serendipity, sensemaking and creativity in the realm of interaction design (Table 6).

| **Concept** | **Description** |
|---|---|
| C#1: A Serendipitous Mind | Focuses on enhancing designers' perceptions and sensemaking abilities in complex situations, advocating for a cognitive approach to cultivating serendipity |
| C#2: The Design of the Process | Involves integrating mechanisms of serendipitous elements into the design of the process, fostering an environment conducive to flexibility, adaptivity and innovation |
| C#3: Serendipitous Team Dynamics | Examines how team dynamics and collaborative processes can be optimised to foster serendipity, enhancing collective creativity and problem-solving abilities |
| C#4: The Generative Role of Tools | Highlights the role of design tools as facilitators in the exploration of design complexity, underscoring the importance of hands-on engagement with design materials and tools for a deep and intuitive exploration of design challenges |

Table 6: Overview of the Four Concepts Describing the Cultivation of Serendipity

This structured approach aims to present a comprehensive overview of the research outcomes, highlighting the underlying patterns, relationships and implications that emerged from my study. It not only enhances understanding but also provides a framework for further analysis, interpretation, and practical application of the findings. The concepts underline a broader perspective of the qualities, mechanisms and conditions contributing to serendipity cultivation in interaction design and how they aid in navigating design complexity.

## 5.1 CONCEPT #1: A SERENDIPITOUS MIND

A particular facet that emerged during my analysis of the case studies is formulated as the concept of 'cultivating a serendipitous mind', delving into the realm of human cognition and mindset when navigating design complexity. First, I explore how a Brunswikian lens model (Figure 8 in Section 2.3.8) can be used to understand how serendipity is cultivated through cognition by what I call *serendipitous cues*. I define these as unexpected chance encounters with information or data, that we stumble upon during cue sampling, akin to what S. Brinkman (2014) calls 'stumble data'. Such cues introduce uncertainty and surprise and thus deviate from established patterns and challenge the conventional cue-to-criterion mapping in decision-making.

I explore the lens model in four steps by connecting my findings to the four key aspects in the process of experiencing serendipity defined in my theoretical framework: being attentive to serendipitous cues, recognising serendipitous patterns, seizing serendipitous opportunities, and creating conducive conditions for serendipity. For each of these aspects, I apply an adoption of the lens model to illustrate how designers make sense of serendipitous cues in the design process. I seek to explore patterns in how cues were integrated into the designer's decision- and sensemaking, the extent to which the designers' understanding of these cues aligned with the development of design hypotheses and whether there were opportunities to improve the utilisation of serendipitous insights in the design process. It is important to emphasise that a lens model is not considered a process model describing a step-by-step sequence. It illustrates an ongoing nonlinear perception process of how the serendipitous cues influence decision- and sensemaking. I have separated the four different aspects of this process into four models to give a clear overview. Further, I propose intentional qualities that designers can develop and apply at an individual level to enhance the cultivation of serendipitous cues.

These findings are based on the analysis of how the cognitive process and these qualities were employed, reflected upon, and articulated in the case studies. Additionally, they draw from an analysis of three peer review sessions with team members (as described in Section 3.6.3). It is important to note that the evidence supporting these findings is limited due to the inherent subjectivity of serendipity as an experiential phenomenon and the relatively small number of participants in my case studies. Therefore, this serves as an initial attempt to contextualise the cultivation of serendipity from a cognitive perspective, providing a foundation for further discussions and investigations.

### 5.1.1 Attentiveness to Serendipitous Cues

Attention patterns play a central role in fostering serendipitous outcomes (Thompson & Copeland, 2023). In the analysis of the case studies, I discovered that the way we directed and managed our attention influenced our ability to perceive *serendipitous cues* within the environment. According to Brunswik (1952), attention is guided by the cues and information available in the environment. In the context of this discussion, serendipitous cues refer to unexpected signals or fragments of information encountered during the exploration of the case study. Within the *achievement* component, we had a set of specific design goals and objectives that shaped our actions and decisions throughout the design process. Brunswik's lens model suggests that attention and perception are not deterministic processes but are driven by probabilistic reasoning. In simpler terms, individuals make judgements and decisions about where to focus their attention based on the likelihood of achieving successful outcomes. However, since serendipity, by definition, involves unexpected and unlikely events, a different approach to managing attention is needed to detect serendipitous cues. I propose an adapted lens model emphasising how the designer's scope of attention in perceiving serendipitous cues is central (Figure 20).

In this lens model, the right focal point represents here the designer as decision-maker or sense-maker, and the focus is on the management of attention towards serendipitous cues. The left focal point represents the case studied, which here represent the case studies. The lens consists of proximal and distal cues and is here represented by serendipitous cues. The achievement arrow represents how effectively the designer can use the cues to understand the case they are examining. A higher achievement would indicate a better ability to utilise unexpected or chance encounters to make sense of the broader situation or problem.

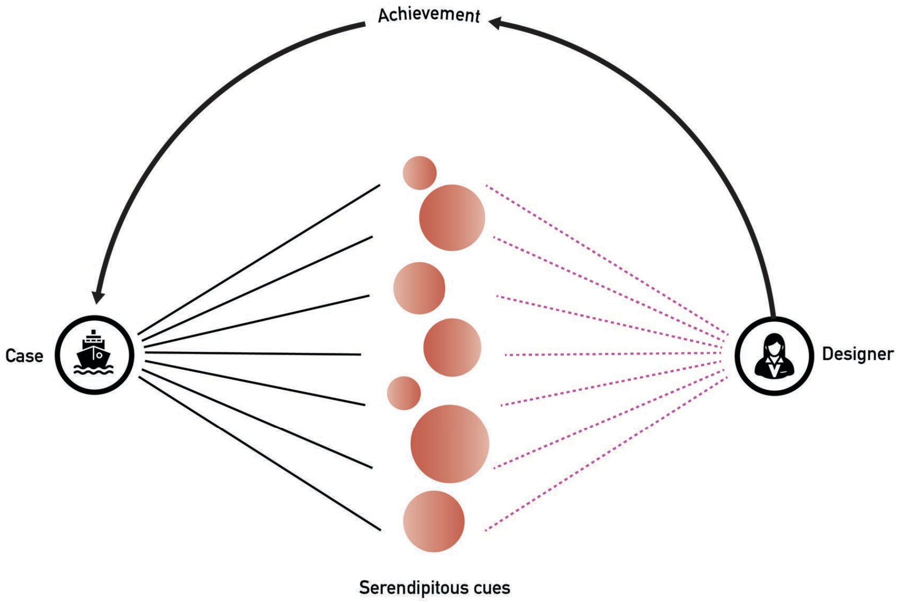



**Figure 20:** Lens model 1: Attentiveness to serendipitous cues.

In analysing how we managed our attention towards serendipitous cues, I have assessed aspects related to the achievement arrow in the model described as three distinctive findings.

### Processing of Raw Sensory Data as Familiarisation

The perception process began with the reception of *sensory information* from the environment through our senses, such as seeing, hearing, or sensing something. For example, during design-driven field research (as discussed in Publications 1 and 2), my firsthand experience was a sense of being overwhelmed due to a broad attention scope. This initial stage of *processing raw sensory data* without necessarily interpreting its meaning or significance can be described as *broad awareness* or *attention* directed towards serendipitous cues without actively recognising or connecting them or knowing where to place the data in our mental framework. The team members suggested that the process of perceiving and storing unsorted cues demanded a significant cognitive workload. However, they regarded this process an important part of familiarisation with the cases, especially during design-driven field research.

**Receptiveness to Diverse Cues**
I found that remaining receptive to cues that might not align with our preconceived notions or expectations is essential for achieving ecological validity, as it allows us to recognise the complexities of real-world situations. However, given the inherent complexity and uncertainty in our cases, our expectations were often vague, necessitating an open-minded approach to diverse cues.

**Anchors amid Uncertainty**
Despite various uncertainties, several aspects were also certain, such as our design expertise and experience with change in previous design processes, working as anchors for managing our attention. The team members emphasised that this anchoring and reanchoring was essential for their capability of working with uncertainty and 'daring to be out of balance'.

When examining the individual qualities necessary for managing attention towards serendipitous cues in design-driven field research, it becomes evident that *observational skills* are paramount. These skills encompass *sustained attention*, *the ability to regulate cognitive processes* and *patience*. For instance, I discovered that when dealing with complexity and focusing on incremental iterations, the persistence to maintain concentration on demanding and time-consuming tasks was crucial.

Moreover, early in my research, I recognised *inquisitiveness* as a fundamental trait for fostering serendipity in the field. It signifies an extraordinary drive to seek fresh insights and interpretations and engage in thoughtful questioning (Watson, 2015). As demonstrated in Publication 2, an 'inquisitive mind' was exemplified by involving users and demonstrating a willingness to reach out to others for extensive problem exploration. As a facet of the broader term 'sagacity', inquisitiveness is crucial for remaining *open* to serendipitous cues. This 'openness' extends to embracing the unexpected and even 'accepting ambiguity' as part of the process of cultivating serendipity, as suggested in Publication 2. Expanding on this idea in the context of attending to serendipitous cues, I propose that retaining cues that are not yet recognisable or whose placement in our mental framework is uncertain can prove valuable at a later stage.

### 5.1.2 Recognition of Serendipitous Patterns

I define recognising serendipitous patterns as the process of associating serendipitous cues with potential value. This potentiality can be understood as being influenced by both inherent factors and social constructs (Busch, 2022b). According to the Brunswikian lens model, it can also be influenced by a combination of probabilistic (related to statistical patterns) and distal cues (related to the environment). Recognition goes beyond mere sensory perception and involves *higher-level cognitive processes* where we interpret and *make sense* of the cues we have paid attention to. While I define paying attention to serendipitous cues (as described in Section 5.1.1) as a broad sensory-driven process, I consider the recognising process a more selective focus based on our perceived significance. This notion aligns with the concept of a prepared mind – a highly discussed term in serendipity research (Vantomme & Crassous, 2021). To illustrate the recognition of serendipitous cues in a lens model, it happens as a synthesis performed by the designer resulting in a new understanding, perception or judgement gained from the case (Figure 21).

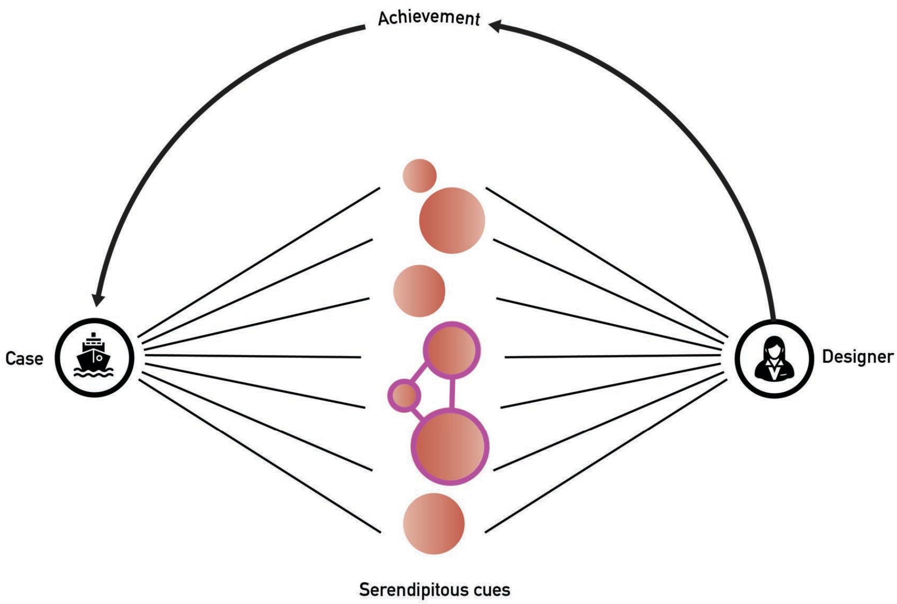



**Figure 21:** Lens model 2: Recognition of serendipitous patterns.

Upon assessing the achievement of recognising serendipitous cues based on analysing the case studies and peer review sessions, five vital findings came to light.

**Discerning Serendipitous Cues: A Filtering Challenge**
Though our evaluation processes, we aimed to distinguish genuinely serendipitous cues from random occurrences or noise. An example of such a cue could be an information fragment, often difficult to recognise immediately due to its incompleteness. This form of sorting was performed by employing *sensemaking techniques* to integrate these cues into our mental representation of the case. The team members suggested these techniques involved their engagement with the materials of the situation. This engagement included activities such as prototyping, evaluating heuristics, performing contextual inquiry when in the field and discussing with end users or domain experts.

Moreover, team members experienced that the usage of these techniques were based on their ability to internalise previous experience in an abstracted manner allowing a generalised application of knowledge in a new context, aligning with Schön's (1984 p. 60) 'repertoire'. By mentally constructing new analytical frameworks or patterns based on previous experience, they were able to develop a refined 'filter' for serendipitous cues. This way, we consciously relied on *probabilistic reasoning* based on our past experiences and knowledge to integrate cues. However, due to the unique nature of our cases, we encountered challenges in this assessment at the outset of the case studies. Consequently, we integrated a high number of random cues while probably missing relevant and serendipitous ones, especially in the initial phases.

**Identifying Serendipitous Cues amid Deviations and Anomalies**
The team members frequently encountered serendipitous cues that appeared as deviations from established norms, posing a significant challenge in their recognition. For instance, during the initial exploration of various placement and appearances of AR graphics in the dynamic and bright environment of a ship bridge, our preconceived expectations how to best design for AR were substantially challenged. Simultaneously, we identified several cues that deviated from our original plans, proving to be unexpectedly useful. Remaining open to these deviations and discerning their potential value was crucial, relying on our capacity for surprise. This concept is consistent with the insights of Turner and Kasperczyk (2022) and Piñyero (2022) – who suggest that a certain level of naivety and detachment from the material or approach is necessary to trigger moments of insight, often described as 'aha' experiences. The absence of well-defined norms,

stemming from a scarcity of design precedents, further complicated our ability to distinguish norms from deviations.

**Enhancing Pattern Recognition and Cue Filtering Over Iterations**
Despite the intricacies of design complexity in relation to serendipitous cues, the team members observed that our capacity to calibrate our attention and filter cues improved with each iteration. This ongoing improvement significantly enhanced pattern recognition abilities.

**Aspects of the Recognition Process**
Given the wide scope of our attention, our cue collection was initially diverse and extensive, making the recognition process ‘messy’, nonlinear and intersecting between overlapping cases. Despite a tendency to seek reduction of the complexity, the team members emphasised that this situation was necessary and sought for recognising cues as serendipitous. They argued that since serendipity is unexpected, the recognition was often triggered by an external event outside their control, and thus, being opportunistic towards recognising the value of serendipitous cues later was important for accepting a messy recognition process.

Moreover, recognition often occurred delayed or decontextualised from the initial perception. Thus, I propose a connection between the synthesis of serendipitous cues and *incubation*, a widely discussed component in serendipity research (e.g. Busch, 2022a; McCay-Peet & Toms, 2015). Although primarily associated with creative problem-solving processes, incubation can aptly describe the cognitive process following the recognition of multiple cues’ connection to the case, often referred to as ‘connecting the dots’ (e.g. Gilhooly et al., 2012).

Nevertheless, in discussions with team members, it became evident that the recognition of serendipitous cues often involved revisiting previous experiences or knowledge that suddenly became relevant in a new context, such as earlier design exemplars. In this context, another problem-solving concept becomes relevant – *opportunistic assimilation*, which posits that unsuccessful problem-solving attempts create a ‘failure index’ stored in memory (Seifert et al., 1995). When encountering the necessary cues in the surroundings during idea development, this failure index can trigger a solution. The resolving of such a failure is often referred to as an ‘aha’ moment (Topolinski & Reber, 2010).

> **Contextualising Serendipitous Cues for Relevance**
> I found that serendipitous cues often needed to be viewed in the context of a larger picture to be perceived as relevant. Awareness of the *broadness and coevolving problem formulations* in the cases enabled us to better assess the relevance and potential impact of unexpected cues.

In Publication 2, we propose the concept of 'sufficient background knowledge', which is akin to having a prepared mind. This means being able to consciously draw upon our existing knowledge in a given situation while recognising its inherent limitations. Designers often rely on their own practical experience, observations, and subjective insights rather than rigid scientific principles (Goodman et al., 2011). Successful designers tend to prioritise subjectivity over academic objectivity in their decision-making (e.g. Moggridge, 2007; Sengers & Gaver, 2006).

Considering this, my research revealed that becoming familiar with unfamiliar contexts and novel interaction materials through field research was crucial in dealing with the unique design complexity discussed in all my publications. This process expanded our designerly ways of understanding and responding to these specific design challenges. It enhanced our ability to recognise and categorise serendipitous cues by developing our pattern recognition skills and interdisciplinary knowledge. This form of embodied learning provided us with an understanding of the users' behaviour within their specific context. It was informed by both social and physical cues in the environment, leading to a contextual understanding of our target users' situations. Additionally, it laid the groundwork for further ideation and prototyping activities.

This perspective underscores the context-dependent nature of recognising serendipitous cues. For example, in Publications 1 and 2, we describe how navigators must multitask, monitoring the oceanscape while managing ship bridge systems. The demanding cognitive workload and complex conditions make it challenging for designers to identify serendipitous cues remotely. Our interactions with the crew played a crucial role in recognising serendipitous cues, emphasising the need for designers to immerse themselves in users' contexts for experiential learning and improved cue recognition. Both the subjective and situated form of *processing information* by acquiring knowledge about users in the field relied on our ability to store information in ourselves, not only *cognitively* but also through our body. For example, exploring the material agency of AR in the moving environment of a ship's bridge contributed to developing our embodied understanding. Lurås and Nordby (2015) refer to this understanding as *designer's sea sense*. This way, I found that contextual learning contributed to recognising serendipitous cues as part of an *internal categorisation* of the context, users, problem, and material.

### 5.1.3 Seizing Serendipitous Opportunities

I define the act of seizing serendipitous opportunities as the process of materialising the potential insights or outcomes that arise from serendipitous cues. This step encompasses various stages, starting with the initial management of attention towards these cues and their recognition. This leads to decision- and sensemaking as designers determine the best approach to achieve desired goals, considering the integrated cues and objectives. The process involves the designer's response to these recognised cues, which includes interpreting and categorising their meaning and relevance within the context of their work. They integrate the serendipitous insights into their sensemaking and problem-solving processes and engage in experimentation with new ideas, solutions or approaches based on the serendipitous cues. Subsequently, they implement changes or adjustments into their work, guided by these cues. In the end, this process culminates in the development of a new design hypothesis, which essentially represents the best-educated guess influenced by the serendipitous cue. This newly formulated design hypothesis serves as an intentional step in the sensemaking journey with the aim of comprehending the case and moving closer to the desired design outcome through *intervention*. As Dalsgaard (2014) underscores, design is essentially an interventionist discipline where the goal is to transform the situation to make sense of it. In essence, responding to serendipitous cues marks the stage where designers actively reshape the case through design interventions. This entire process is visually depicted in my adapted lens model (Figure 22). Here, I introduce the 'design hypothesis' as a new element, signifying an outcome of the designer's sensemaking. Furthermore, an arrow illustrating transformation extends from the design hypothesis to the case, emphasising its transformative significance.

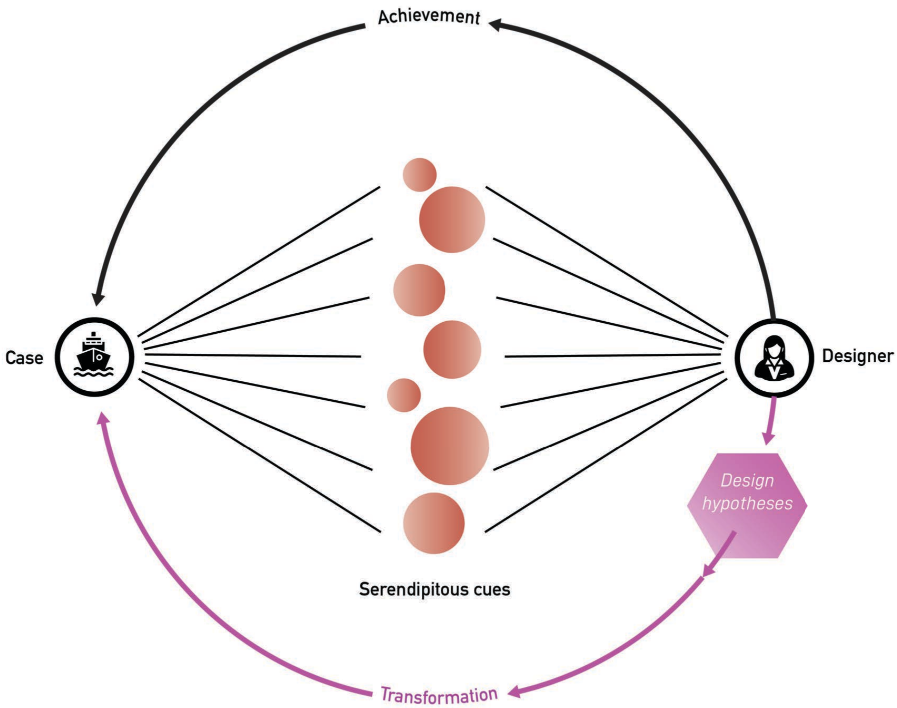



**Figure 22:** Lens model 3: Seizing serendipitous opportunities through the formulation of design hypotheses.

In assessing the 'achievement' of seizing serendipitous opportunities based on managing attention towards and recognising serendipitous cues, three significant insights surfaced.

### Leveraging Opportunism

Team members highlighted the pivotal role of opportunism in seizing serendipitous opportunities. Embracing an opportunistic approach to timing allowed us to tap into external events that could supply the necessary resources for seizing serendipitous opportunities. For instance, when opportunities such as gaining access to field research trips, external expertise, equipment, or funding presented themselves, team members carefully considered the timing for capitalising on these externally initiated events to respond to serendipitous opportunities. This adjustment required a shift in our perception of the case when evaluating its potential significance. In the initial stages, this sometimes led to seemingly random selections of focus areas for design potential and constraints. However, as familiarity with the cases grew, our ability to strategically time our actions regarding serendipitous opportunities significantly improved, highlighting an increase in achievement.

**Transformation and Discovery**
I noticed that as we delved deeper into the integration and exploration of unexpected cues through design hypotheses, our perception of the case often experienced significant shifts, leading to the revelation of new patterns or connections that were not initially apparent. An illustrative example of this feedback loop can be observed in a serendipitous cue that initially guided our focus towards exploring the design of information related to the ocean's surface on the side of the vessel. This, in turn, expanded our attention scope, unveiling new serendipitous cues.

**Experiential Learning**
Team members suggested that our ability to integrate serendipitous cues into our decision-and sensemaking process was fortified through experiential learning. By encountering, recognising, and responding to unexpected cues that lead to favourable outcomes, they asserted that their proficiency in identifying and acting on serendipitous cues likely improved in subsequent work. In this context, one team member proposed that the capacity to seize serendipitous opportunities hinges on designers' intuition – which, in turn, draws from their design repertoire to discern whether something is genuinely novel and valuable rather than merely novel to them.

In Publication 2, we harnessed the traits of *opportunism*, involving the proactive pursuit of chance opportunities, and *explorativeness*, which entails actively seeking and discovering serendipitous opportunities, to define our approach to design-driven field research. These characteristics rely on our ability to draw from our design repertoire as designers and be confident in its applicability within the appropriate context and timeframe, a concept in line with Schön's (1984) insights and Busch's (2022) definition of self-efficacy as an enabling attribute for serendipity cultivation. Furthermore, opportunism can be associated with Rivoal and Salazar's (2013) concept of the ability to recognise the right timing as a crucial factor for serendipity in field research.

Another instance highlighting the interplay of opportunism and explorativeness is the innovative teaching approach described in Publication 6. The context was the COVID lockdown – which prompted both teachers and students to adapt their teaching and learning methods, making use of new technology platforms. The outcomes revealed that students adhering to traditional learning paradigms faced challenges in fully utilising their limited resources, identifying opportunities and capitalising on serendipitous moments. In contrast, opportunistic students, despite their unfamiliarity with the technology, effectively explored and recognised opportunities within their constraints. They leveraged unforeseen potentials, leading to the discovery of innovative prototyping techniques.

In Publication 2, we introduced the concept of allowing creative distractions as a strategy for serendipitous design-driven field research. Creative distractions can be viewed as serendipitous cues that facilitate the emergence of new problems or ideas, potentially leading to serendipitous outcomes. Within this strategy, I emphasise the significance of spontaneity as a personal attribute. In our work related to design complexity, I observed the occurrence of multiple problem-solving processes unfolding concurrently, albeit in different stages. The adoption of a systematic approach could limit spontaneity in switching between these processes due to rigid plans. Conversely, an approach geared towards cultivating serendipity allows for flexibility and exploration. This perspective resonates with Stolterman's (2008) concept of designers being prepared for action rather than being overly guided by predefined plans and methods. In such a context, adapting to the richness and complexity of the situation takes precedence over adhering to predetermined plans and approaches. Therefore, the cultivation of serendipity requires not only the ability to pay attention to or recognise cues but also the willingness to act upon them, regardless of the task at hand.

'Good timing' is explored and substantiated in Publication 2. When examining how this concept can be translated into individual qualities and skills, based on my observations of team members and personal experiences, it becomes evident that these qualities involve quick thinking, the ability to think on one's feet and respond promptly to serendipitous cues. Intuition, encompassing a gut feeling or instinct that suggests taking action in the moment, plays a crucial role. Additionally, decision-making skills come into play as individuals evaluate the potential of serendipitous cues and determine the most appropriate course of action. Optimism is also a significant factor, as it involves believing that acting upon a cue can result in a valuable outcome.

'Creative thinking' as an individual prerequisite for a serendipitous approach is also suggested in Publication 2. In analysing the case studies, I identified that the team members' creative mindset, combined with an uncharted design space devoid of established guidelines, created favourable conditions for acting upon serendipitous cues by abductive reasoning. When navigating novel technology and a complex domain, our lack of familiarity and experience necessitated challenging conventional thought. This highlights how employing abduction to address design complexity, such as serendipity, thrives on thinking nonlinearly, embracing potentialities, and intuitively connecting seemingly disparate components. This underscores the cognitive interplay between generating inventive explanations and chancing upon valuable insights.

### 5.1.4 Creating Conducive Conditions for Serendipity

I define the process of creating conducive conditions for serendipity as actively shaping the environment to enhance the chances of encountering serendipitous cues. Unlike the previous three steps, this stage does not follow a linear progression but instead embraces a continuous and broader perspective. It revolves around the intentional actions that designers can take to create or modify the *boundary conditions* of the situations to increase the likelihood of serendipity. Boundary conditions here mean the external factors or constraints that define the context within which designers work on a given case. I propose that it is the interplay between these diverse factors and the individual that gives rise to serendipity. Based on the analysis of the cases, I argue that essential boundary conditions in the situations studied include the physical environment in which we worked; the interaction material (AR) we were engaged with and its formgiving considerations; the project management that regulated aspects such as time, budget, resources, access and requirements; the creative process entailing specific guidelines, objectives, research questions and problem-solving methods; and domain-specific regulatory constraints and stakeholder specifications.

Additionally, I draw on Busch's (2022) theorising about the cultivation of serendipity, suggesting that timing and event strength are significant boundary conditions. Events that are novel, disruptive, or critical can disrupt established thought patterns and lead to unexpected changes that 'catch us by surprise' (Morgeson & DeRue, 2006). The timing of the serendipitous cue needs to align with the designer's current goals and priorities. In the final lens model (Figure 23), the boundary conditions are emphasised as the environment around the designer and the case.

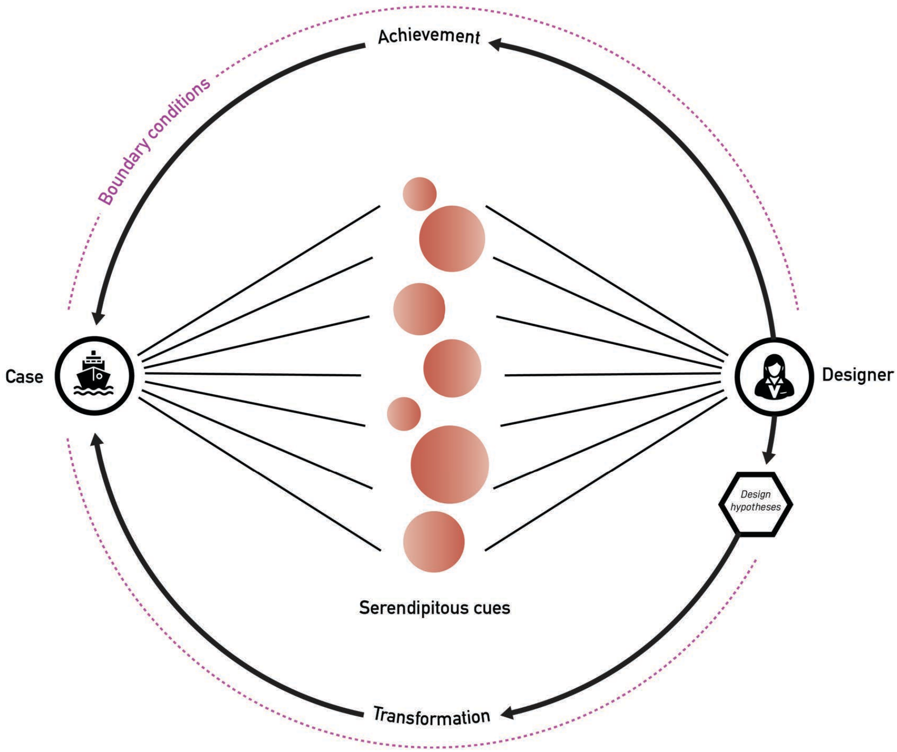



**Figure 23:** Lens model 4: Creating conductive conditions for serendipity.

When evaluating the impact of creating conductive conditions for serendipitous cues on our sensemaking process, the analysis of the case studies and the peer review sessions revealed five important findings.

**The Interventionist Role of Design**
Design aims to bring about change by introducing novel elements to modify the existing status quo, as already emphasised in the previous model. Hence, I observed that we consistently exerted influence on the situations studied and many of their boundary conditions through our design interventions. For instance, in the earliest case studies, we initially regarded the formgiving concerns as uncertain boundary conditions, implying that guidelines and precedence were not established. However, through our exploration of how formgiving influenced the case through design hypotheses, we were able to shape and redefine these concerns by defining guidelines and heuristics and developing exemplars. By acknowledging the inherent dynamism of

conditions in design complexity, we harnessed our role as interventionists to intentionally cultivate serendipitous cues.

**Unsteady Boundary Conditions and Flexible Organisation**
The boundary conditions played a crucial role in defining our problem scope and navigating the possibilities within our given context. However, I observed that the design complexity encountered in the case studies often featured somewhat unstable boundary conditions. For instance, the creative process was influenced by unresolved design requirements, leading to an unclear scope. Consequently, to gain a clear understanding of these boundary conditions, the projects were structured to facilitate extensive exploration, which resulted in the discovery of multiple unexpected insights driven by serendipitous cues. These insights included unanticipated approaches and novel user engagement methods.

A team member noted that in an organisational context this approach is often unfeasible in the industry due to the gap between the mandated project deliverables and the potentially achievable outcomes. Hence, in research projects designed for serendipitous exploration, like those documented in this PhD thesis, resources for opportunistic exploration of potential were allocated in addition to the required research deliverables in each work package, creating a space for context-specific inquiry. Such organisational flexibility, which contributed additional value to the overall project objectives, became feasible through the concurrent development of cases and projects, as this approach ensured overlapping and shareable outcomes across both.

**Contextual Immersion**
I discovered that immersing ourselves in the field, whether in the physical setting or within the VRROS, significantly increased our ability to incorporate temporal, physical, and spatial cues from the real or virtual environment into our conceptual framework while formulating design hypotheses. For instance, when we worked with design hypotheses related to the UI appearance in the ship bridge environment, we became more attuned to new cues emerging from our design interventions and integrated these cues into our overall understanding of the case.

In this context, I found that design-driven field research greatly heightened the probability of recognising serendipitous cues arising from social interactions, events, and environmental conditions. This was due to the occasional density and diversity of cues in the ship bridge workplace – which offers a wealth of sensory information, including movement, people, and operational activities. Furthermore, the strength of these cues was amplified by our perception of their criticality or potential for innovation in our study involving navigators using a novel technology within a complex domain.

**Timing**

In exploring the facets of timing, I discovered its dual nature, requiring both strategic patience and the ability to respond decisively. During field research, a considerable amount of time was dedicated to being present on the bridge, awaiting the perception of potential serendipitous cues. Similarly, I observed that prompt action based on such cues, in the right moment, could lead to significant outcomes. Thus, establishing conducive conditions for timing hinges on a framework that delicately balances strategic patience and responsive decisiveness. Proactive presence (refer to the management of attention in Figure 20) facilitates the capture of potential serendipitous cues (see recognising serendipitous patterns in Figure 21), aligning seamlessly with the agility to seize opportunities promptly (see Figure 22). This dynamic interplay ensures not only the establishment but also the effective leveraging of conditions for optimal timing in serendipity cultivation.

By integrating strategies for proactive waiting and swift action within the process, the team navigated the delicate balance necessary for effective timing. This involved incorporating anticipatory measures – such as dedicating specific periods for patient observation and remaining open to unexpected cues, as exemplified in the field research. Additionally, fostering an Agile mindset ready to act decisively when serendipitous opportunities presented themselves contributed to the flexibility needed to adapt to the temporal constraints inherent in the design process.

**Manipulation of Boundary Conditions through Tools**

I found that the conditions of serendipitous cues perceived from material (AR) engagement could be *manipulated through tools*. For example, by revisiting situations in the VRROS, we could enter with different attention managements or improve our ability to recognise serendipitous cues. In addition, by using tools to generatively produce multiple versions of a prototype, we were able to explore a form of *randomness* leading to unexpected perceptions of the case. This finding is elaborated further in Concept #4 The Generative Role of Tools.

User involvement can be a valuable means for designers to develop empathy and gain insights into the user's situation (e.g. Fischer et al., 2020). *Social skills* play a crucial role in this context and are considered enabling qualities in cultivating serendipity (Busch, 2022b). A way of employing our social skills was by incorporating tools and methods that allowed end users to ideate or experiment collaboratively with us. I found that such approaches created conditions where we directed our attention towards cues representing diverse perspectives and needs that we might not have otherwise considered, given our professional and personal backgrounds, cultural norms, and values. For instance, during one of the field trips, we utilised paper prototyping as a technique to cocreate an optimal ship's bridge with the ship leader (Figure 24).

**Figure 24:** Cocreating with end users during Design-Driven Field Research

In the coreflection sessions following the field trip, team members emphasised the vital role of diverse social skills in cultivating serendipitous cues within the study. These skills encompassed various aspects of communication, including effective verbal and nonverbal expressions demonstrated using rough paper prototyping. For instance, I observed that an introverted person could offer a more nuanced set of cues by critiquing an experience prototype than by abstractly envisioning an idea or describing their personal experience. Therefore, displaying empathy emerged as an essential component of these social skills, involving a demonstration of interest and sensitivity. This could be facilitated in the process through active listening, characterised by our full attention and relevant questioning. Moreover, familiarity with the appropriate etiquette and respect, which includes adherence to social norms and conventions, was crucial in expressing empathy. An illustrative example is our entrance into the coastguard vessel KV Svalbard, representing a military institution with strict etiquette and procedures. It was imperative to familiarise and adapt to this environment to conduct socially skilled field research (see Publications 1 and 2).

In a broader analysis of our case studies, I found that psychological flexibility played a pivotal role in our ability to respond constructively to change, especially when it deviated from our initial plans or goals. For instance, when a domain expert highlighted errors in the order of events or misunderstandings during the evaluation of scenarios for VRROS (see Publication 5), we needed to swiftly adapt both our mental map and practical approach to the case, allowing us to be receptive to new cues. This led to fresh perspectives and premises that enriched our problem-solving process, offering novel ways to comprehend both the problem and potential solutions. Additionally, cognitive flexibility, involving the capacity to shift focus and manage multiple tasks or problems simultaneously, played a pivotal role in creating conditions conducive to serendipitous cues.

### 5.1.5 Summary of the Concept

Concept #1 explores the influence of what I define as *serendipitous cues* on the sensemaking process of designers in the case studies. I used four lens models to illustrate how serendipitous cues in the environment are perceived. These models recognise that the impact of serendipitous cues on the constructs and outcomes (design hypotheses) can be uncertain. This implies that cues may not always lead to the desired results and that decision-making and sensemaking processes can entail varying levels of uncertainty. Assessing the effectiveness of integrating serendipitous cues can be complex. Hence, the primary aim of introducing the lens models is to conceptualise the cultivation of serendipity from a cognitive perspective, emphasising the perceptual role of serendipitous cues in the sensemaking of design case.

## 5.2 CONCEPT #2: THE DESIGN OF THE PROCESS

This concept describes how a process can be designed to effectively grapple with uncertainty, change and unexpectedness when navigating design complexity. It is not enough that a team member identifies serendipitous opportunities if the process fails to seize the chance and integrate new information into existing processes, structures, and plans (Ross, 2023). Thus, cultivating serendipity in the design process requires flexible organisational structures that support new ideas and provide room for proactive actions and innovative solutions to emerge. Moreover, these structures need to be integrated through attentional, informational, or material resources (Busch & Barkema, 2022b). For this concept, I investigate what Busch (2022) defines as *resource integration mechanisms* as a key aspect of cultivating serendipity at the organisational level. Using the case studies, I analysed the use of such mechanisms in the design process to elucidate how they coincide with navigating design complexity.

### 5.2.1 An Iterative and Incremental Process

In Chapter 2, I presented the significance of iterations in the context of problem-finding and problem-solving in design. Additionally, Norman (2023) proposes that the design of complex systems, consisting of numerous interconnected components, could greatly benefit from an incremental perspective. Given that interaction designers often collaborate with software developers, the former frequently aligns their processes with the latter.

Iterative and incremental methodologies are commonly employed in software development for complex projects (Alsaqqa et al., 2020). Agile methodology, in particular, exemplifies this approach by prioritising collaboration, customer feedback and adaptability to changing requirements (Back et al., 2001). Agile methods emphasise delivering functional solutions in short iterations, integrating feedback and continually adjusting to evolving conditions and demands (Rajlich, 2014).

However, as Agile methodologies were initially developed for software, adapting it to design is essential. This adaptation allows designers to approach complexity with an open mindset and a willingness to explore multiple solutions (Hussain et al., 2009). An examination of the process design in the case studies reveals an Agile interaction design approach, which can be categorised as adapted for practice-led research. Furthermore, the data suggests that this adapted approach encompasses several inherent resource integration mechanisms conducive to cultivating serendipity. In the following, I will highlight four main findings.

**Iterative Learning Cycles**
The case studies were structured around iterative development increments, forming a systematic process of reflection, learning, adaptation, and the integration of new insights. This *iterative learning*

*cycle* facilitated experiential learning, serving as a resource integration mechanism, and allowing the team to effectively incorporate information, data, tools, ideas, and experiences into the process. Consequently, the mental construction of the case, as well as associated goals, methods, and plans, continuously evolved.

### Dynamic Adaptation of Problem Scope: Bridging the Conceptual and Explaining Levels

Our approach of working in smaller, more focused scopes facilitated a seamless shift between active reflection and postaction analysis. It also streamlined the transition between addressing higher-level issues, represented by conceptual frameworks, and tackling lower-level problems through increments. This *adaptive problem-scope mechanism* supported both reflective action and a comprehensive analysis of our actions. I have categorised these two levels as the *principle* and *practical levels* (see Figure 25).

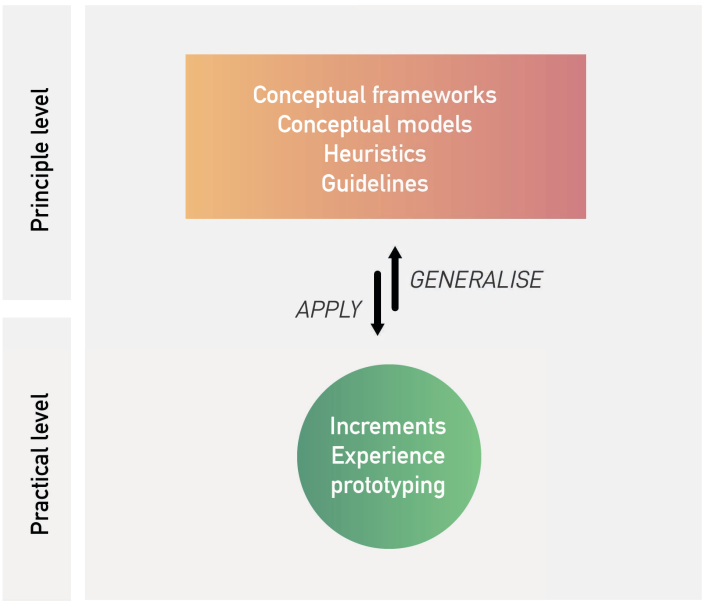



**Figure 25:** Dynamic Adaptation of Problem Scope in Principle and Practical Levels

The principle level encompasses conceptual frameworks, conceptual models, heuristics and guidelines that have been developed based of the practical level, which, in turn, represents increments developed through experience prototyping. This approach can be seen in the light of Schön's concept of developing 'a repertoire of exemplars' as a way of cultivating 'knowing in practice' (1984 p. 274). In this context, this implies that for each practical design exemplar (e.g. the Icebreaker Assistance app in Publication 5), our repertoire from which we could generalise expanded. The generalisation from the practical level is evident in design frameworks, heuristics and guidelines, which are represented at the principle level, as exemplified by the OB design system in Publications 3 and 4. This dual-level approach highlights the dynamic interplay between theoretical constructs and their practical implementation, a key insight derived directly from the data collected in the case studies.

**Dynamic Nature of Design Deliverables in Iterative Processes**

In analysing the frameworks and exemplars, I found that the design deliverables, which typically are considered fixed entities in a design or software development project, acquired a dynamic nature within the Agile iterative design process. This *dynamic nature* functions as an essential mechanism for cultivating serendipity within the context by adapting to the unexpectedness, uncertainty and change inherent in design complexity. For example, concepts and frameworks presented in Publication 1 were significantly altered through multiple iterations in Publications 4–6. Similarly, the proposals for the OB design system presented in Publication 3 underwent multiple versions and extensions. Hence, the deliverables represent only the status quo. This shift in perspective reframes the traditional understanding of deliverables as permanent endpoints.

**Deliverables as Design Hypotheses**

The previous finding highlights the role of design deliverables as fluid *design hypotheses* (Bang et al., 2012), a foundational construct within abductive reasoning (Dorst, 2011). Although not explicitly expressed as design hypotheses in the publications, the deliveries were considered dynamic conceptualisations of our best guesses, each holding the potential to incorporate serendipitous ideas and insights in the next iteration. For example, the UI architecture for AR presented in Publication 4 represents a design hypothesis for a conceptual framework, while the app proposal presented in Publication 5 represents a design hypothesis of an exemplar. The mechanisms related to design hypotheses are the *flexibility and adaptability* of the design deliverables, which allowed us to adapt and refine our deliverables in response to new discoveries and insights that emerged throughout the iterative processes. By designing a process where design deliverables remain open to change and adaptation, these mechanisms enhanced the receptivity to serendipitous cues, ultimately leading to the generation of innovative solutions and insights.

**A Hands-On Approach**

The case studies revealed a challenging situation for us as designers. On the one hand, we faced an information overload when dealing with the domain, and on the other hand, there was a lack of information regarding the interaction material. Instead of waiting for more comprehensive research, which might never be entirely satisfying, we chose to adopt a hands-on approach. This approach allowed us to actively engage with materials and users, as exemplified in our design-driven field research described in Publications 1 and 2, as well as our teaching efforts outlined in Publication 6.

By going hands-on, we activated mechanisms such as *active immersion, physical interaction,* and *sensory stimulation*, significantly enhancing our engagement with the external world. As discussed in Concept #1, this heightened engagement with the environment triggered a multitude of sensory cues – including serendipitous ones, which became essential building blocks for our sensemaking process. In essence, the hands-on approach can be considered a form of abductive reasoning that provides opportunities to test and refine initial hypotheses. Moreover, it provided central mechanisms for integrating serendipitous cues into our creative process.

Employing these mechanisms created conditions conducive to serendipity. Our interactions with users, experts and colleagues led to responses and insights that purely observational and noninterventional methods might not have uncovered. A concrete example of the effectiveness of these mechanisms is presented in Publication 6, where we describe an interaction design course utilising the VRROS platform. Despite students' limited background knowledge and experience in interaction design materials, those who embraced the hands-on approach reaped the benefits. They discovered new ways to make sense of the design context and material, grounded in a 'quick-to-solve' mindset and a readiness to engage with incomplete information. This approach embodies essential mechanisms for continuously integrating resources and insights, thereby cultivating serendipity.

### 5.2.2 Multiple and Overlapping Case Studies

Given that the case studies were conducted concurrently with significant overlapping focus, they functioned in a state of coevolution. Coevolution, commonly applied in the Agile development of complex software systems (Vidgen & Wang, 2009), draws parallels with the reciprocal interactions observed in biological systems.

In the context of the case studies, I define *coevolvement* as a dynamic and reciprocal mechanism for the integration of convergent resources. This process involves the continuous adaptation and mutual influence of design hypotheses, which represent tentative solutions or strategies for designing complex systems. Both levels of design hypotheses function as data to inform one another, creating an iterative and recursive process that interweaves analysis and generation. This mechanism proves particularly valuable when dealing with significant interdependencies among various design elements, such as frameworks and exemplars. For instance, in Publications 3 and 4, we introduced the initial version of the OB design system, which later underwent multiple iterations as a result of its application to exemplars.

To conceptualise the mechanisms for resource integration in the coevolution of the case studies, I propose a model that illustrates this process in four stages (Figure 26). Like Figure 25, this model consists of two levels representing the conceptual and explaining levels. The iterative and recursive arrows signify the best guess of application and generalisation between the two levels. In the following sections, I will describe the coevolutionary mechanisms in these four stages.

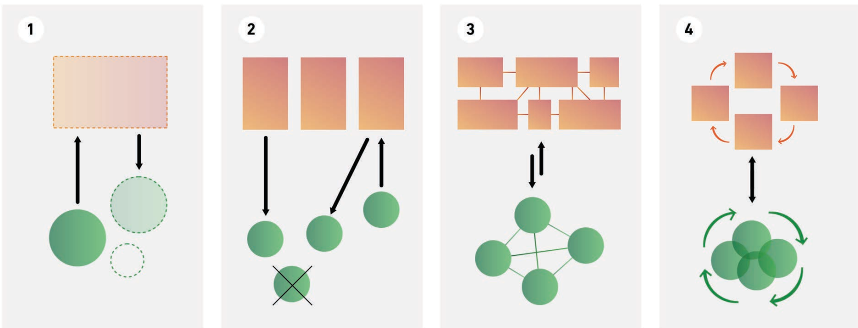



**Figure 26:** Four steps of Coevolution of Design Hypotheses in Principle and Practical levels.

**1 Starting point**
A few design hypotheses (based on increments) were developed and coexisted in the same environment for experience prototypes (e.g. VRROS) relying on the same uncertain foundation for requirements for designing and formgiving concerns. Here, uncertainty was at its highest, and the openness to integrate serendipitous cues was wide. For example, we started off with a design framework hypothesis representing the few requirements for designing and formgiving concerns that we found sensible, and we had two design hypotheses representing a part of the system, like an application.

**2 Competition and interaction**
As different hypotheses started to function together as a whole, changes made to one component could affect the behaviour or requirements of other components. These early iterations and initial tests revealed that different hypotheses supported various requirements and concerns, while others were selected away. For example, we iterated on the design frameworks and divided them into three different design frameworks covering various application areas, such as consistency, the placement of information and palettes. We iterated on the hypothesis for multiple parts of the system.

**3 Mutualism and feedback loop**
After several iterations, the hypotheses complemented each other and created a mutualistic relationship where changes in one component triggered adaptations or modifications in related components. For example, if a framework required adaptation or extension to be applied on a specific component containing new requirements for designing or formgiving concerns, the framework had to be adopted to accommodate this change and had to be reapplied to the other components constructed from this framework.

**4 Coevolution and continuous integration**
As the mutualistic relationship strengthened, each hypothesis (both exemplars and frameworks) continued to iterate in response to the others' adaptation. The uncertainty was low; still, accommodating change was important, and chance opportunities were perceived easily.

This coevolution mechanism facilitates the open integration and testing of new and unexpected insights and ideas. Consequently, I found that maintaining a low threshold for serendipitous integration in this process also means a low threshold for elimination after testing, thus reducing the risk of persisting with dead-end ideas.

### 5.2.3 Examples from the Case Studies

To concretise the mechanisms of the coevolution of design hypotheses, I will in the following highlight concrete instances from the case studies to illustrate its real-world applicability (see Figure 27). Notably, the development of the Icebreaker Assistance app within the AR system showcases the deliberate approach of engaging with complexity through a subincremental strategy on the practical level, breaking down the task into smaller subtasks that focused on individual variables (Publication 5). Each part and variable underwent gradual development to ensure the creation of a testable prototype for usability testing in the VRROS. Likewise, the evolution of the OB design system exemplifies the adaptive nature of design frameworks representing the principle level, a direct reflection of the process of continuous application and generalisation (described in Publication 3 and 4).

**Figure 27:** The Icebreaker Assistance application as an example of the practical level to the right and the OpenBridge design system as an example of the principle level to the left. (Photo: OICL).

### 5.2.4 The Temporal Aspect as a Boundary Condition

In incremental design processes, improvements occur progressively over time, with each design increment forming part of an evolving system of interventions (Hvidsten & Almqvist, 2023). The coevolving iterative and incremental process design described in this concept requires an investment of time, constituting a boundary condition for cultivating serendipity. Many processes aimed at controlling complexity through fixed boundaries often prioritise mitigating unnecessary time consumption. Working with strict boundaries and tight schedules can lead to disruptions and risks when faced with deviations or unexpected events, given little room for adjustment. In contrast, a ‘time-rich approach’ acknowledges time as a valuable resource and allows navigating change with lower risks.

The case studies were based on a time-rich approach, which incorporated more flexibility and adaptability into the process. This approach allowed for extra time and leeway to respond to unforeseen circumstances, integrate new insights and address changes without causing significant disruptions or risks to the project. This process design shares similarities with Agile methodologies in software development, where iterative and flexible processes enable teams to adapt to changing requirements and priorities as they arise.

The passage of time naturally leads to alteration. Framing the design problem is a fundamental aspect of incremental design, resulting in continuous redefinitions of both the problem and its solutions as the design process unfolds (see, e.g., Dorst, 2015b; P. H. Jones, 2014). This necessitates adjustments to the understanding of ‘WHAT’ and ‘HOW’ based on previous increments and iterations. This gradual alteration is exemplified by the evolving problem definitions and solutions in the framework development and formgiving exploration throughout the publications.

### 5.2.5 Summary of the Concept

This concept explores how to design a flexible and adaptive process to effectively handle uncertainty and complexity in design. It emphasises the importance of identifying serendipitous opportunities and integrating them into the process. Key mechanisms from the iterative and incremental process, where learning and adaptation occur continuously, include an iterative learning cycle; the dynamic nature of design deliverables, viewed as fluid hypotheses; the flexibility and adaptability of design hypotheses; the coevolution of design hypotheses, allowing for mutual influence and adaptation; and a time-rich approach that acknowledges time as a valuable resource. These mechanisms collectively contribute to the cultivation of serendipity within the design process, enhancing its responsiveness to unexpected insights and ideas.

## 5.3 CONCEPT #3: SERENDIPITOUS TEAM DYNAMICS

At the core of this concept is the recognition that cultivating serendipity in design is a deliberate collective endeavour. *Mechanisms* for cultivating serendipity in teams can be dependent on the quality of social integration (Busch, 2023). Here, serendipity can arise from the abilities and collaborative integrations of multiple individuals (Cunha, Clegg, & Mendonça, 2010). Since serendipity depends on connecting previously unrelated information and ideas, it is more likely to occur in group environments that encourage meaningful interactions enabling individuals to grasp the broader significance of an unexpected discovery (Busch & Barkema, 2022a).

In analysing the mechanisms of social integration and collaborative synergies in the case studies, I found that our approach had similarities with the values of the Agile Manifesto (Back et al. 2001). The iterative and incremental nature of the Agile management of a process can be beneficial in addressing complexity (e.g. Sohi et al., 2016). However, it is important to emphasise that this thesis is not considering Agile adopted to interaction design from the perspective of a collaborative process with software developers but from the perspective of practice-led research by design.

In the previous concept, I noted that the design of a process is influenced by Agile core principles of an iterative and incremental structure. In this concept, I analyse the case studies through the conceptualisation of design values adopted from the Agile Manifesto to explore mechanisms for social integration and collaborative synergies. These adapted values can be considered fundamental in guiding decision- and sensemaking and supporting the mechanisms for cultivating serendipity.

### 5.3.1 Value #1: Individuals and Interactions over Processes and Tools

It is evident from the data that a way to recognise the potential of serendipity in team interaction is that each personal encounter holds the potential of chance. Through collaboration with and observation of my team members' collaborative efforts in the case studies, I found that the team members' role in driving the creative process and adapting to the changing user needs through direct communication was key in cultivating serendipity. Social networks have the potential to facilitate serendipitous encounters by expanding the volume and variety of interactions (McCay-Peet & Toms, 2015). These can lead to the emergence and exchange of unforeseen ideas (Busch, 2023).

In analysing the case studies, I found that one effective mechanism for facilitating the OICL's social network digitally was the use of Slack, which enabled features such as real-time messaging, channels, threads, file sharing, integration with other tools, search functionality and notifications. It was utilised for collaboration both within the team and with external stakeholders, and it fostered a high frequency of information sharing with a low threshold for insights and experiences.

Additionally, the *physical facilitation* of social networks plays a pivotal role in fostering serendipity (Björneborn, 2017; McCay-Peet & Toms, 2018). This occurred through day-to-day activities within the lab, where shared workspaces and lab facilities were utilised, as well as during workshops, partner collaborations, user testing in the lab, fieldwork, and participation in events throughout the case studies.

I observed that these two mechanisms for promoting social interaction significantly contributed to a seamless exchange of ideas among individuals within the internal and extended teams. Importantly, this exchange was not driven by predefined processes or specific goals but rather evolved naturally based on the inherent need for interaction and idea exchange. It was during these interactions between individuals with diverse perspectives that unexpected connections and insights often emerged. Busch (2023) suggests that social embedding can potentially enhance the occurrence of serendipity. Therefore, these two mechanisms, which foster collaboration among team members and stakeholders, played a key role in cultivating serendipity and encouraging *organic interactions*. In contrast to strictly directed or goal-oriented processes, this mechanism hinges on the innate need for interaction and idea encounters.

However, the degree to which the organisation of the team's social network facilitates serendipity is contingent on both the team culture and the shared intellectual and field interests of the team members (Lane et al., 2021). Upon analysing the case studies, I observed a common research focus and a strong motivation and interest among team members in exploring the problems within the case studies. My data does not definitively explain why this shared interest developed, as such an understanding would require a more in-depth study beyond the scope of the case studies. Nonetheless, von Hippel and von Krogh (2016) suggest that a team sharing a common problem formulation plays a pivotal role in how individuals identify, filter, and prioritise emerging ideas. Therefore, it is reasonable to argue alignment of the team's shared focus on the design of AR for ship bridges and the novelty of the research problems – enabling extensive exploration of the 'WHAT' and 'HOW' – likely contributed to a significant potential for active engagement and for making an impact.

Furthermore, I found that the external interest from stakeholders (as described in the development of the OB design system in Publications 3 and 4) and end users (as described in the field study in Publications 1 and 2 and the usability study in Publication 5) enhanced the perceived significance of the work among team members. Consequently, this team culture likely facilitated a readiness to engage in open, creative discussions and informed decision-making and fostered a sense of ownership in the complex problem-solving environment at the OICL.

### 5.3.2 Value #2: Functional Prototypes over Comprehensive Documentation

In this value, the term 'working software' has been substituted with 'functional prototypes'. The analysis of the case studies underscores the significance of early prototyping in exploring both requirements for designing and formgiving concerns. Figure 28 depicts the scenario where a navigator is testing an early prototype using the HoloLens as part of design-driven field research. In my definition, a prototype is considered functional when it enables the designer to effectively communicate a UX to the participant, eliciting valuable feedback and facilitating an exploratory discussion. All publications demonstrate the effectiveness of experience prototypes and concept sketches for testing and evaluation. By analysing this, I found that prototyping holds several mechanisms for cultivating serendipity in a team. First, I found that functional prototypes allowed team members to interact directly with a *tangible representation of an idea*, sparking unexpected insights and ideas during hands-on exploration. Second, since prototypes prioritise UX, they encouraged the team members *to view the design from a user's perspective*, holding the potential of discovering serendipitous improvements based on user interactions. Third, because prototyping supports *iterative design*, it enabled us to experiment, make quick changes and stumble upon innovative solutions that may not have been apparent through static documentation. Fourth, the process of creating and testing prototypes often involved *collaborative learning* – where we shared insights and perspectives, facilitating serendipitous discoveries through discussions. Fifth, the functional prototypes facilitated the *collection of real user feedback data* – which uncovered unanticipated user preferences, pain points or needs, guiding serendipitous design adjustments to the hypotheses. Sixth, the prototypes *visually communicated* design ideas, making it easier for the team members to see and understand the concept and potentially triggering novel thoughts and creative suggestions. Finally, the functional prototypes were used to *actively engage* *end users* in the design process, fostering serendipitous insights as users provided unanticipated input and suggestions.

**Figure 28:** Functional Prototypes as part of Design-Driven Field Research. (Photo: OICL)

We prioritised the use of testable prototypes as a key gauge of project progress. Although prototypes hold more value than documentation in an Agile design process, efficient documentation techniques remained valuable, such as the OB design system and frameworks (Publications 3 and 4), field research documentation (1 and 2) and methodological documentation (1, 2 and 6). However, I found that the *dynamic setup* for adjusting and expanding the documentation according to prototype development was key. As an example, the OB design system is documented in Figma, functioning as a living document that can distribute updates to all application components.

### 5.3.3 Value #3: Partner Collaboration over Project Agreement

I have replaced 'customer' with 'partner' to encompass both business and research contexts in this Agile value. Further, I have translated 'contract negotiation' to 'project agreement' to make the value applicable in a broader sense. Traditional design processes models, such as Waterfall, involve partners primarily at the beginning and end of a project, where product requirements are extensively discussed before any work begins (Alshamrani & Bahattab, 2015), whereas the Agile model involves industrial partners throughout the project, providing continuous feedback and establishing ownership by incorporating their guidance at all stages.

All publications consider design complexity in the context of partner collaboration. By analysing this, I found that partner collaboration holds several mechanisms for cultivating serendipity in a team. First, the collaboration with partners often involved individuals from different backgrounds and disciplines, increasing the *diversity of perspectives* potentially leading to the emergence of unexpected ideas and solutions. Second, in some instances, collaborating partners brought knowledge and practices from their respective domains, leading to *cross-pollination* of ideas and methods. An example of this is our use of eye tracking to get insight into the user's attention during field research (Publication 1). While the partner who borrowed us the equipment used it to collect quantitative data to generate attention patterns, we discovered that the data we collected also had value to us in a qualitative perspective, as well as in a dersignerly perspective by providing real-world first-perspective video for the prototyping of AR concepts. Third, sometimes, partners engaged in *shared exploration and experimentation* – such as through the development of VRROS (5), which can uncover unexpected opportunities and solutions that may not have been part of the original project agreement.

Fourth, I found that the collaborative efforts had the potential to extend beyond the initial project scope – leading partners to *explore adjacent or related areas*, where serendipity can manifest. The OICL research projects clearly illustrate this mechanism – where a quite consistent partner group continuously extends the scope of previous or existing projects, resulting in new research projects. For example, SEDNA was an extension of OB but for AR, while OpenAR can be considered a continuation of SEDNA. Fifth, I found that the *frequent interaction* with diverse partners and end users contributed to facilitating an open collaborative design process where our design hypotheses gained broader resonance.

Finally, by *taking advantage of the partner network*, the team members obtained access to important resource integration mechanisms, such as *effective evaluation* and *direct resourcing* (Busch, 2023). This enabled the team to recruit domain experts (Publications 3–5), conduct field research (1 and 2) and involve partners in workshops and meetings for knowledge sharing (1–6). We were thus able to use various *codesign* techniques with partners, such as paper prototyping, sketching, scenario building and VRROS. Despite potentially lower feasibility scores, codesigned concepts exhibit higher usability and innovation (Trischler et al., 2018), which are valued in Agile design.

### 5.3.4 Value #4: Responding to Change over Following a Plan

Analysis of the response to change in the case studies revealed several mechanisms I suggest holds a potential for cultivating serendipity in a team. First, I found that several aspects already described, such as *iterative exploration* (described in Concept #1), *open communication* (described in Values 1 and 3), *iterative and experiential learning* (described in Concept #1 and #2) and *embracing uncertainty* (Concept #1) also function as key mechanisms for the cultivation of serendipity directly linked to responding to chance. Second, I found that the aims and problem definitions were formulated as wide and adaptable, thus allowing for *flexibility in the problem-solving*. As opposed to highly specific problem definitions and rigid plans, less narrowly defined problems and flexible plans tend to enhance the ability to spot and capitalise on unforeseen chances (McCay-Peet & Toms, 2010b). For example, in Publication 1, we describe the aim as exploring the possibilities and constraints of designing for AR in a maritime context through field research. This aim can be characterised as highly wide since we do not define what we mean by possibilities and constraints or the scope of collection. While the background for this loosely defined aim was the low degree of agreement according to requirements for designing and the uncertainty according to formgiving, the potential was to embrace change and uncertainty through adapting the problem-solving approach dynamically, thus increasing the likelihood of serendipitous occurrences emerging from unexpected directions.

Third, I found that making *opportunistic and flexible plans* helped us prepare how to explore our wide aims and problems. By acknowledging that change and uncertainty is an unavoidable asset of a design complexity and embracing the challenges and richness it provides (Stolterman, 2008), iterating in short time spans meant that plans could be revised according to priorities for each iteration. I found that planning was a continuous process and that changes represented a value in that they required adaptation resulting in a multifarious exploration. For example, during field research

(Publications 1 and 2), we encountered change and unpredictability in the working environment deriving from factors such as operations and weather. Since rigidly predefined plans often fail to account for the complexities and contingencies of real-life situations, field research cannot be neatly planned in advance and executed as if isolated from the surrounding context (Suchman, 1985). To address this, we prepared adaptable tools and diagrams in advance, allowing us to adjust our research activities on the fly. For instance, we created ship bridge diagrams that could be modified digitally and on paper during visits, aiding data collection, interviews and codesign sessions (Figure 29).

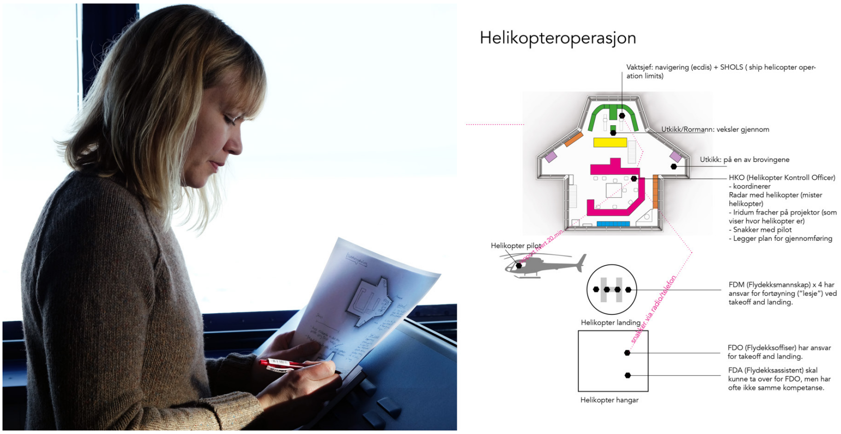



**Figure 29:** Premade ship bridge diagrams used flexibly in various data collection situations during design-driven field research. (Photo: OICL)

### 5.3.5 Summary of the Concept

Collectively, the mechanisms outlined within our Agile design approach not only transcend serendipity as a mere happenstance but also imbue it into the core of the design process itself, endowing it with attributes of adaptability, shared ownership, and perpetual learning. This points to the understanding of sensemaking as a collective temporal process, where knowledge is processed by a team over time (Schwandt, 2005; Weick, 1995). As intricacies are unveiled, novel connections emerge, and unforeseen insights surface. The mechanisms direct attention towards the collaborative dimension of design, describing collaborative aspects of addressing design complexity where change is welcomed.

## 5.4 CONCEPT #4: THE GENERATIVE ROLE OF TOOLS

Central to this concept is the idea that chance arises from generative activity, allowing for the emergence of multiple variations, including the unexpected. Repetition and reflection, essential for learning from experiences (M. Brinkmann, 2016), interact with accidental or chance elements, providing a generative impact in the creative process (Piñeyro, 2022). However, when evaluating recent comprehensive theories on cultivating serendipity (e.g. Busch, 2022b), the mechanisms within materials, viewed from a pragmatic technology perspective, are not emphasised. In the field of design, the tools we employ play an instrumental role in extending and enhancing our human capabilities. Therefore, they significantly influence how we interact with the environment, solve problems, gain knowledge, and, consequently, cultivate serendipity. Through an analysis of the case studies, I aim to elucidate these mechanisms within the generative role of tools.

*Design tools* encompass a variety of physical or digital components that enable designers to work with materials or extend their capabilities (Daalhuizen et al., 2019). These tools can take the form of devices or software used in creating, manipulating, or facilitating the formgiving of interaction materials. The term 'tool' is employed to describe a set of techniques or approaches for using a device or software for a specific purpose. Generative tools, often associated with computer algorithms and AI, utilise these technologies to generate a multitude of options based on defined parameters and constraints, as seen in the example of ChatGPT (Stokel-Walker & Van Noorden, 2023). In the realm of design, Sanders (2000) defines generative tools for co-designing as visual and verbal components arranged in toolkits that enable users to create diverse artefacts expressing ideas. In this thesis, the term implies that a tool can generate numerous variables through methods like paper prototyping, rough-tech prototyping, or more advanced combinations of software components to create experience prototypes, without necessarily involving AI and algorithms.

Before I present the mechanisms for cultivating serendipity using generative tools in the last part of this concept, I first offer an overview of the generative tools employed in the case studies and their application in the upcoming sections.

### 5.4.1 Mediating Experiences through VRROS

Upon analysing the case studies, I observed that generative tools can act as crucial intermediaries in shaping human experiences, as demonstrated in Publications 5 and 6. To illustrate this, I will use the VRROS as a representative example to describe four examples. The configuration of the VRROS is comprehensively explained in Publication 5 and visually depicted in Figure 30. In this figure, a study participant can be seen wearing the HMD and holding the controllers used for navigating the scenario to the left, while the scene experienced in VR HMD is shown to the right. Given the limited availability of authentic real-world contexts in the maritime sector, there is significant untapped potential for exploring how the UX of maritime applications can be impacted using scenarios as generative tools.


**Figure 30:** The Setup of the Virtual Reality–Reconstructed Operation Scenarios (VRROS). (Photo: OICL)

#### VRROS as a Tool for Prototyping

In Publications 5 and 6, we demonstrate the pivotal role of VRROS as a prototyping tool. The VRROS setup encompasses various defined surfaces and areas suitable for different UI designs, fostering serendipitous exploration. These defined areas are based on design hypotheses, refined through multiple iterations to determine optimal placements of AR elements according to SA. The model allows flexibility, enabling the addition or adjustment of surfaces and areas as needed. Through direct editing in Figma and model updates, we tested crucial variables like appearance, temporality, consistency, and conditional states. Given the simulation of diverse user interactions and conditions, the VRROS facilitated exploration along varied paths, leading to the discovery of unexpected ideas, problems, or solutions not initially considered—a testament to its capacity for cultivating serendipitous exploration.

### VRROS as a Collaborative Tool

Publications 4 and 5 showcase the VRROS as a valuable tool for collaborative design and user engagement. Its swift generation of new design conditions allowed for immediate collective exploration and evaluation. The VRROS's effectiveness lay in inspiring spontaneous exploration, fostering unexpected insights. Acting as a collaborative workspace, it transcended geographical boundaries, enabling seamless global collaboration. This inclusivity expanded expertise and perspectives, fostering chance interactions and insights sharing. The immersive nature of VR, replicating real-world scenarios, enhanced our team's ability to make well-informed decisions by providing a deeper understanding of the UX (Figure 31).

**Figure 31:** VRROS as a collaborative tool together with external partners in the lab. (Photo: OICL)

### VRROS as a Tool for Manipulation

In Publications 4, 5, and 6, we explored diverse design hypotheses using the VRROS, manipulating scenes for generative exploration. Adjusting factors like daylight, weather, and buoyancy created varied output conditions impacting the UX. Time manipulation allowed us to shift between moments or play scenarios in slow motion, offering unique insights distinct from real-world experiences. The platform's capability to capture still shots or short sequences guided user attention for targeted evaluation. Through evaluating hypotheses across conditions, unexpected design flaws and enhancement opportunities emerged, contributing significantly to refining formgiving concerns and potentially leading to improved and safer ship bridge UIs.

**VRROS as a Tool for Virtual Fieldwork**

In Publication 6, we detail how the VRROS acts as a versatile tool, serving as preparation, enhancement, and, to some extent, a substitute for onsite ship bridge design-driven fieldwork in teaching interaction design students (Figure 32). The efficient accessibility facilitated quick familiarisation with operations, system understanding, and context-based prototyping. The rapid, generative approach not only speeds up the process but also enhances intuition for serendipitous discoveries, fostering creative insights and unexpected opportunities.


**Figure 32:** Students using the VRROS as a tool for virtual fieldwork and prototyping in the research-based teaching course. (Illustration: Henrikke Roaldsnes Ulvlund, Ragnhild Fjeldberg and Sephira Iona Barfai Bjørndal)

Together, these four examples of VRROS describe the mediation of experiences in various ways that may cultivate serendipitous exploration.

### 5.4.2 Rough-Tech Prototyping as a Generative Tool

During design-driven field research, we explored the cultivation of serendipity through forms of experience prototyping I call rough-tech prototyping of AR UIs. Even though there exist many design systems for screen-based UIs, such as OB design systems, they are not directly applicable to AR. One example of employment of such a flexible method was carried out by two team members on a research expedition to Svalbard outlined below. The last two steps contributing significantly to our findings in Publications 4–6.

**Step 1: Initial Sketching**
We began with paper sketches based on the OB design system, simplifying the visual representation of instruments (see Figure 33). These sketches provided a low-effort, quick, and efficient way to categorise UI content and gather navigator feedback.

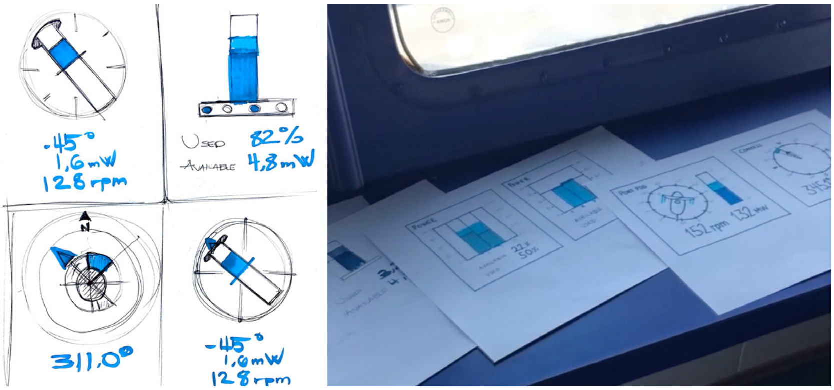



**Figure 33:** Paper sketches based on OpenBridge design system drawn and captured through HoloLens. (Photos: OICL)

**Step 2: Transition to AR Prototyping**
Next, we translated these paper sketches into AR prototypes using photos of the sketches (Figure 34). This allowed us to test various UI combinations, placements, appearances, and sizes within the HoloLens, catering to different contextual conditions. Navigators' feedback informed continuous adjustments and iterations.


**Figure 34:** Scanned paper sketches and video screenshots from AR based on OpenBridge design system drawn and captured through HoloLens. (Photos: OICL)

### Step 3: Advancing to Realistic UX

To enhance the prototypes' realism, we integrated digital simulator components directly from the OB design system, converting analogue paper sketches into digital vector graphics (Figure 35). This step brought us closer to achieving a genuine UX and aligning the prototypes with actual user needs. Expert users and research partners further refined these concepts in the lab.

**Figure 35:** Illustration of how the navigator sees the digital UI components through HoloLens drawn and captured through HoloLens. (Photo: OICL)

This process describes a flexible method that helped us navigate the complex exploration formgiving concerns of AR and resulted in valuable serendipitous insights, contributing to the research outcomes presented in Publications 4, 5, and 6.

### 5.4.3 The OB Design System Used as a Generative Tool

In the analysis of the case studies, I discovered that generative tools could facilitate practical knowledge application (Publications 3–6). To contextualise this, I will use OB design system built in Figma (Version 3.2.1) as an example. *Design systems* are collections of design elements and guidelines that ensure consistency across multiple designs (Fessenden, 2021). Although some designers worry that design systems may limit their creativity (Beck, 2019), there is an increasing perception in the field of interaction design that well-designed design systems provide a framework for generating new designs that conform to a certain set of rules and guidelines, as well as being adaptive to change (Mall, 2023). The OB design system is based on an iterative development of translates requirements of designing into formgiving concerns shaping a responsive and consistent system of graphical elements, navigations patterns, logic, and appearance. This way, OB represents in-built knowledge generalised in a tool that can be used to generate multiple specialised use cases.

The OB design system was built in Figma (Version 3.2.1), a web-based design tool that allow users to create and collaborate on digital designs, including UIs, webpages, and mobile applications. The OB design system has been developed to contain numerous *UI patterns*, including alerts, application, settings and microapps; *palettes*, including typography, colours, and styles; and *components*, including navigation, application, and automation. While Figma is not typically considered a generative tool, there are ways in which it can be used for generative design, through functions in building a design system. For example, Figma was used to create reusable components, which can be used to generate new designs quickly and easily. By creating a library of components, we could quickly generate multiple variations of a design by swapping out different components. Moreover, with Auto Layout, Figma allowed us to define relationships between objects, such as their spacing, alignment, and resizing behaviour and to create dynamic and adaptive designs that respond to changes in content or screen size. Finally, Figma has a large library of plug-ins that can be used to automate repetitive tasks and generate design options. For example, we have used plug-ins such as *Able* (for verifying colour contrast according to WCAG [Web Accessibility Initiative, 2018]), *Material Symbols* (for standard Google Material icons), *Unsplash* (for CC images), *Color style guide* (to generate the Palette library setup based on the Figma colour styles) and *CSSgen* (to export a CSS code library of our colour styles).

Below, I provide three examples on how the OB design system was utilised as a generative tool to apply generalised knowledge to specific use cases.

**OB Design System Connected to VRROS**

We integrated the OB design system into Figma and VRROS, seamlessly incorporating transparent surfaces into the 3D scene using Unity or Unreal Engine (see Figure 30). Our approach involved connecting the desired Figma UIs to these surfaces as textures from a Dropbox folder. Leveraging VRROS, we had the flexibility to experiment with different positions and visual styles for AR UIs by adjusting the surfaces within the 3D scene, showcasing UIs imported from Figma. This virtual setup empowered us to work effectively with AR UIs in a lifelike environment, generating a multitude of variations with minimal effort. This approach significantly broadened our scope for discovering chance opportunities.

For the team members, this setup served as a swift means to explore and assess UI prototype variations. It enabled us to uncover aspects of the OB design system that didn't directly translate from web-based screens to AR applications, leading to a proposal for augmenting the OB design system for AR (Publication 4). Moreover, we made substantial progress in our research by involving project partners and end users in evaluations and user testing through this setup (Publication 5). Rapidly applying the OB design system to various operational and contextual conditions within VRROS allowed us to continuously assess its suitability for the case studies. This ongoing testing played a pivotal role in shaping the development of the OB design system. By streamlining our workflow and creating an immersive testing environment, we maximised our potential to uncover chance opportunities and enhance the OB design system's adaptability for AR applications.

**Exploring OB Design System in Teaching**

When analysing how students engaged with AR UIs, utilising premade components from the OB design system in Figma alongside VRROS recordings to communicate their conceptual UX (as discussed in Publication 6), I observed an efficient progression beyond mere graphical UI design. Instead, students were able to delve directly into the realm of interaction design by iteratively modifying and expanding upon various UX alternatives (Figure 36). Notably, some students employed Adobe After Effects to integrate these UIs into scenario recordings, providing their peers with a vivid and realistic portrayal of their concepts. It is important to note that many of these students possessed little to no prior experience with design systems or with VR or AR. However, those who took advantage of the tools and the course's setup found them invaluable for exploring diverse interaction design possibilities within a constrained yet complex problem space.


**Figure 36:** Students utilise the OpenBridge design system to develop experience prototypes with the VRROS in the research-based teaching course. (Illustration: Henrikke Roaldsnes Ulvlund, Christel Røshol and Christoffer Nydahl)

### Applying Research to Industry

In analysing the application of an OB as a generative tool to industry along with the case study progress, I found that the continuous feedback and application examples gained from implementations by industry partners worked as mechanisms for integrating external chance opportunities (Figure 37). This can be explained with, the wider application area, the more requirements for designing, such as industry regulations, was incorporated in new iterations of the system.


**Figure 37:** Application of OpenBridge Design System from the Industry Partner Alphatron JRC. (Photo: OICL)

### 5.4.4 Mechanisms for Cultivating Serendipity through Generative Tools

Upon analysing the mechanisms for cultivating serendipity using generative tools in the case studies discussed in the previous sections, I found several distinct aspects.

#### Exploring Design Variation and Diversity

In several of the case studies, AR technology played a pivotal role as an interaction material influencing formgiving concerns. To systematically explore diverse material qualities, we developed generative tools capable of manipulating variables within the experience prototypes. Variables such as text colour or interactive visualisation duration were subject to manipulation, with values representing specific data or characteristics assigned to these variables (e.g. the colour code '#4285F4' or '30 seconds'). This intentional manipulation allowed us to probe the expansive range of these variables, uncover dependencies among them and, consequently, generate a multitude of prototype versions. Given that prototypes consist of multiple variables, the use of generative tools significantly amplified the production of design exemplars, thereby enriching our repository of potential solutions. This iterative process, functioning as a mechanism, not only bolstered our capacity for reasoned decision-making in forming design hypotheses but also fostered the serendipitous discovery of unexpected results within the various prototype versions.

### Effective Evaluation

Organisations employ various strategies to assess unexpectedly emerging ideas, such as intuitive flash evaluations (Napier & Vuong, 2013). The generative tools described earlier serve as platforms for evaluation by generating experience prototypes. These tools not only allowed us to manipulate parameters and constraints but also provided high-fidelity prototypes, enabling the rapid creation of diverse and realistic variations in the experience prototypes. This way, the tools facilitated a mechanism of *effective evaluation* of our best guesses and serendipitous ideas. The evaluation process involved collaboration among team members, end users and stakeholders, fostering a collaborative synergy for iterative assessment of the experience prototypes. This approach supported comprehensive and effective exploration, enabling us to evaluate a wide spectrum of design possibilities and identify optimal solutions. The tools, such as the OB design system and VRROS, enhance precision in evaluation, requiring less effort compared to traditional nongenerative design methods. Throughout our iterative processes, the mechanism of effective evaluation honed our attention to serendipitous cues and the recognition of serendipitous insights.

### Exploring Complex Design Outcomes

The VRROS provided numerous inputs for constraints and design criteria, resulting in a wide range of outcomes in the exploration prototypes. However, I often encountered challenges in foreseeing the effects of even minor adjustments in the design of distributed augmented UIs due to the complexity of cause-and-effect relationships. This complexity arises from the contextual immersion of graphics and the intricate interrelation between components. Consequently, the difficulty of predicting complex outcomes in the experience prototypes prompted the rapid adoption of the ‘employ-to-explore’ mechanism for experiential learning. By ‘employ-to-explore’, I refer to the hands-on experimentation process of configuring parameters (such as conditions in the VRROS) and utilising premade elements (such as the OB design system). Subsequently, we allowed the tool to generate an outcome for evaluation. While this approach is not based on randomness, it can lead to unexpected outcomes through generative tools because design complexity challenges the ability to foresee all possible outputs. This is exemplified in Figure 38, which displays a screenshot of multiple variations within a UI exploration.

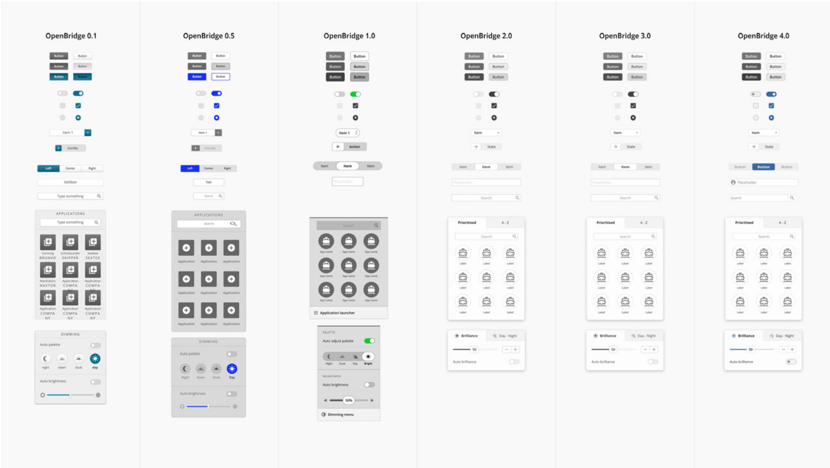



**Figure 38:** Screenshot of Multiple Variations within a UI Exploration in Figma. (Photo: OICL)

## Transformative Learning through Failure

Utilising randomness to foster serendipity in the process led to an increase in unexpected outcomes, many of which were initially perceived as failures. This observation holds significant implications. The perception of failure often arises when intentions and expectations do not align with the intervention's outcome (Piñeyro, 2022). However, in the initial stages of the case studies, our expectations regarding the final outcomes of the experience prototypes were unclear due to design complexity. Consequently, inherently unexpected results could swiftly shift the perception of failure to a relevant finding.

As the research progressed and our expertise in formgiving concerns developed, the perception of failure resulting from the use of generative tools became more distinctly regarded as a learning mechanism. Lock and Sikk (2022) suggest that failures can motivate designers to explore unintended opportunities. This perspective aligns with the opportunistic assimilation theory, where a failure index can trigger a solution through new cues from the environment (Seifert et al., 1995). I discovered that a way to harness the discomfort of failure in navigating complexity was by making deliberate adjustments through repetitive actions.

The coevolutionary structure of the case studies, as described in Concept #2, resulted in a reservoir of so-called failure indexes in the team members' minds, poised to be triggered across different cases. Here, it became clear that failure has a transformative nature. I found that the mechanism of turning failure into learning depended on the repetitive development of experience prototypes, easily facilitated through generative tools. This process drew on reiteration and the recall of past knowledge framed slightly differently by the tools, resulting in new insights. Viewed from a Deweyan perspective, this form of learning-as-experience can be understood as transformation through repetition (M. Brinkman, 2016).

### 5.4.5 Summary of the Concept

Concept #4 describes how tools play a generative role in cultivating serendipity. It recognises that tools expand designers' capabilities and influence problem-solving and knowledge acquisition. The concept introduces generative tools, explores their roles in case studies and outlines mechanisms for cultivating serendipity, including diverse design exploration, effective evaluation, the exploration of complex outcomes and transformative learning from failures. In essence, it emphasises how tools contribute to serendipitous discoveries in interaction design.

# 6 DISCUSSION: SITUATING THE CULTIVATION OF SERENDIPITY WITHIN A COMPLEXITY LANDSCAPE

In this chapter, I seek to contextualise and analyse the potential of cultivating serendipity within the broader landscape of complexity. My goal is to elucidate the implications, insights and new perspectives that arise by placing these two critical concepts side by side. The discussion revolves around the strategic approach to cultivating serendipity within the context of design and in conjunction with the unexpected. Moreover, I discuss how design complexity can be navigated through the conceptualisation of a complexity matrix model used to categorise complexity into five zones. Through a nuanced examination, I aim to uncover the practical significance of serendipity in addressing the multifaceted challenges presented by design complexity, as well as its relevance in the realm of interaction design and beyond. This discussion serves as a bridge between the theoretical underpinnings explored in Chapter 2 and the practical implications explored in Chapters 4 and 5, highlighting the potential transformative power of serendipity in complex design processes.

## 6.1 SERENDIPITY AS A STRATEGY FOR INTERACTION DESIGN

Cultivation implies a strategic approach towards serendipity. In this section, I address theoretical perspectives on purposefully cultivating serendipity for design by discussing my results (Concepts #1–4) of the second subsidiary research question: In what ways can serendipity be deliberately nurtured and integrated into the interaction design process to enhance sensemaking and creative outcomes? The section serves as a guide to navigate the intentional integration of serendipity into the design process by emphasising its strategic relevance in intersection with the unexpected seen from four perspectives.

### 6.1.1 Hands-On Exploration of Design Materials

In the quest of cultivating serendipity, a hands-on approach with interaction materials becomes effective. Viewing design as an exploratory generative process means that we are open to serendipitous discoveries, even when things do not go as planned. Piñyero (2022) suggests embracing failure in hands-on interactions with materials, seeing them as possessing their own agency. In relation to this, Copeland (2022, pp. 54–56) discusses our approach to serendipity presented in Publication 2, suggesting it is an example of how *material manipulation* can be a relevant approach for intentionally incorporating serendipity into research. She argues that our multifaceted approach and innovative problem-solving methods, as evidenced in design-driven field research, create an environment conducive to serendipity. Aligning with Robert Merton's (1948, p. 507) notion of a 'serendipity pattern' in sociological research, this approach hinges on unexpected, yet strategic, observations that instigate the development of new theories.

Merton (1948) suggests the observer plays a crucial role in recognising the value of the unexpected data and utilising it to extend theory or explore new research directions. This way, cultivating serendipity in pragmatically approaching design complexity requires domain knowledge, material exploration and the insight to understand how new information can transform the case. However, serendipity patterns can be considered a strategic approach to serendipity because they appear first when the designer is acting upon a chance encounter (Copeland, 2022), as highlighted by the four lens models presented in Concept #1.

### 6.1.2 Leveraging the Interaction of the Prepared Mind and Chance as a Strategic Approach

The prepared mind can be characterised by sufficient background knowledge, an inquisitive mind, creative thinking and sensitivity for timing, as suggested in Publication 2. Still, it is in the intersection with the unexpected we need to strategically employ these qualities in a relevant way to yield serendipitous outcomes as described in the examples (Publication 2). This way, contemplating serendipity as a strategic pursuit accentuates the dynamic interplay and manipulation between individuals and the world (Copeland, 2022). It involves an orchestrated synergy between the prepared mind and chance (McCulloch, 2022).

In Concept #1, I explored cognitively how the prepared mind responds to chance through cues in the environment. McCay-Peet and Toms (2015) explains this attentiveness to cues as responsiveness to external triggers. In her discussion of our serendipitous approach presented in Publication 2, Copeland (2022) suggests that it entails gaining a strategic advantage over chance while pursuing one's intended goal:

> Thus, rather than design for serendipity itself, the group [OICL field researchers] approached serendipitous design innovations as something that

> emerges from the context when we focus on inclusion and iteration, and attend to the limitations of our own understanding and imagination. The techne here is a craft of reshaping one's strategies and methods in response to what happens along the way to one's goals; setting out the criteria above, the research team is attempting to formulate a set of guidance or heuristics meant to ensure the right kinds of response. (pp. 56–57)

However, in addition to the strategic rationality, as Copeland (2022) defines our research approach, 'cunning wisdom' incorporates practical considerations, including social, contextual, and temporal factors (Detienne & Vernant, 1991). The practical wisdom acquired through experience allows designers to tackle design complexity (Stolterman, 2008). It is an embodied form of reasoning that requires adaptability in mutable and indeterminate settings (Holford, 2020). Holford further suggests several methods for cultivating this type of skills, such as 1) internalising formalised abstract knowledge, 2) internalising situational knowledge, 3) engaging in social practice and dialogue and 4) engaging in repetitive individual practice within real situational contexts involving 'indwelling' (pp. 8–9). Formed as *heuristics* (Yilmaz & Seifert, 2011), this kind of knowledge captures essential elements of problem situations and solutions that tend to reoccur in experiences while applied flexibly according to the situation (Clancey, 1985). This aligns with the pragmatic approach to knowledge-as-practice (Dewey, 1938a) – which I, in Concept #3, discuss how it can be cultivated in a team. This concept highlights the value of collective rationality (Moshman & Geil, 1998) and heuristics (S. P. Turner, 2012). Both can be considered important for social integration mechanisms in cultivating serendipity.

### 6.1.3 Indwelling as a Strategy

Copeland (2022, pp. 62–63) describes our serendipitous approach (Publication 2) as an example of *indwelling*. Understanding the context through field studies is crucial when dealing with design complexity, as human behaviour is best understood within the specific situations and circumstances in which it occurs (Lurås & Nordby, 2015). Situational cues, such as social norms, cultural expectations, and physical environment, play a significant role in guiding behaviour and shaping knowledge acquisition and application (Suchman, 1985). In Concept #1, I introduce the term serendipitous cues, which I contextualise in lens models to describe our approach to indwelling in the case studies. Copeland (2022, pp. 62–63) suggests that we (the OICL field research team), by physically experiencing the conditions and usability of our design in a specific context, were able to gain a unique perspective and respond to unforeseen situations using our expertise. Thus, indwelling can be seen, not merely as a strategy applied from the outside but also as a way of understanding and continuously adapting within the situation by allowing designers to bring their expertise and perspectives to address the problems and opportunities that arise. Here, the management of attention towards serendipitous cues, the recognition of serendipity patterns, the seizing of serendipitous opportunities and generation of conductive conditions for serendipity, as introduced through the four lens models in Concept #1 are attempts to understand indwelling as a continuous cognitive process that shape our sensemaking. Moreover, the qualities suggested in connection to each lens model can be considered enablers for making sense of serendipity.

### 6.1.4 The Role of Generative Design

Central in this concept is the idea that chance stems from a generative activity – giving rise to a multitude of variations, including the unexpected. Doing generative design is an effective method for cultivating serendipity because the activity allows slightly new variables into a situation that can yield serendipitous cues from the people involved, the context or the material. This way, repetition and reflection enables learning from experiences (M. Brinkmann, 2016). In the interplay with the accidental or chance elements, repetition gains a generative impact in the creative process fostering serendipity (Lock & Sikk, 2022; Piñeyro, 2022).

Nevertheless, in evaluating recent theories of cultivating serendipity (e.g. Busch, 2023), I found a gap in describing the qualities and mechanisms from a pragmatic technology perspective. In Concept #4, I address this gap by presenting findings from the analysis of how tools designed in a generative manner enabled serendipity cultivation. Designers' tools have an instrumental role in extending and enhancing their capabilities and are thus significant for how they interact with the environment, solve problems and gain knowledge (Dixon, 2020). This perspective aligns with the famous adage: 'We shape our tools, and thereafter the tools shape us' (Culkin, 1967 p. 53). In this light, understanding the generative impact of tools on the creative process provides valuable insights into how serendipity can be intentionally cultivated through thoughtful design and technology integration. These perspectives outline the dynamic interplay between individual cognition, external triggers, and practical wisdom in the pursuit of innovative unexpected outcomes.

## 6.2 NAVIGATING DESIGN COMPLEXITY

In this section, I seek to discuss design complexity by exploring its dimensions and implications for the field of interaction design by contextualising the results of the first subsidiary research question: *What are the fundamental aspects of design complexity that interaction designers need to comprehend and address?*

### 6.2.1 Intertwinedness of Two Complexity Dimensions

In Section 4.1, I conceptualised design complexity as two dimensions: requirements for designing and formgiving concerns. While the distinction of two design complexity dimensions might seem reductive at first glance, it can serve as a framework for navigating the intricate landscape of design challenges by characterising and distinguishing concrete aspects. It is necessary to see this distinction to understand how they are intertwined.

The intertwinedness of the two dimensions is presented in Section 4.4. To summarise, first, a problem within one dimension can be dependent on a problem in the other dimension. For example, establishing a certain usability requirement can hinge on problems of articulating the formgiving concerns for placement and appearance (as addressed in Publications 1, 4 and 5). Second, a problem in one dimension can cause a new problem in the other dimension. For example, regulations for colour and contrast in a certain palette of maritime UIs constituting requirements that pose a challenge for the formgiving of AR UIs, where these demands are difficult to accommodate due to the concerns of extreme light conditions in the contextual integration. Third, a problem in one dimension exacerbates a problem in another dimension. For example, by intending to provide better SA information to the navigators through the AR UIs by providing numerous data points and graphics, we may have worsened the cluttering of displays or information overload. This intertwinedness implies a dynamic relationship where the factors influencing one another create a complex and nuanced design environment. By acknowledging this intertwinedness, I argue that the dimensions still move beyond a simplistic view of design complexity and recognise the interconnected nature of various elements. This perspective allows for a more holistic understanding, where the dimensions of uncertainty and agreement influence each other in a reciprocal fashion. The intertwined nature of these complexity dimensions suggests that changes in one aspect can ripple through the entire design process, requiring a flexible and adaptive approach. Moreover, this perspective challenges the traditional dichotomy of simplicity and complexity. Instead of viewing them as opposing ends of a spectrum, the intertwinedness suggests a continuum where projects may exhibit characteristics of both, depending on the specific requirements for designing and uncertainties in formgiving.

### 6.2.2 A Complexity Matrix for Design

As described in the Section 2.3, there exists several models aimed at providing a complexity landscape for decision-making, information, biology, mathematics and so on. The Stacey matrix (Figure 9 in Section 2.3.3) acknowledges that the complexity of a situation is not just a function of the number of variables involved but also the social dynamics and relationships among people (Stacey, 1996). This aspect of complexity can already be considered a well-addressed dimension in the field of design, especially concerning the design development of organisational services with a complex stakeholder situation (Hvidsten & Almqvist, 2023). However, I suggest there is also a need to highlight the complexity dimension of certainty in relation to formgiving in design.

The domain of interaction design is presently under the sway of fabricating interfaces designed to convey immersive and meaningful encounters. Simultaneously, it encounters a trifold challenge due to recent advances in hybrid materials that merge the physical and digital (such as AR), the burgeoning complexity of sociotechnical ecosystems and the rising autonomy of systems (Höök & Löwgren, 2021). In recent years, the interaction design sphere has diligently sought novel and more suitable theoretical paradigms that transcend the established usability and practicality ideals, as previously described. These encompass research into the pragmatic aesthetic viewpoint on the nature of UX (Lim et al., 2007; Löwgren & Stolterman, 2007), exploration of concept-driven interaction (Stolterman & Wiberg, 2010), the convergence of pragmatism and design thinking in interaction design (Dalsgaard, 2014) and a deliberate engagement with the material turn (Wiberg, 2018). Höök and Löwgren characterise interaction design as a field in flux due to the emergence of novel materials and technologies and suggest that designs stemming from it permeate various usage domains, necessitating a perpetual demand for innovative design frameworks to grapple with this kind of complexity.

To situate the form of design complexity defined and addressed in this thesis, I propose an adapted model named the complexity matrix for design (Figure 39). It maintains the two dimensions for decision-making, ranging from high to low: *agreement* and *certainty*. In adapting them to design, I apply the abductive reasoning equation of ‘WHAT’ and ‘HOW’, which I defined as *requirements for designing* and *formgiving* in Section 4.1. By distinguishing design in the two dimensions, I propose a perspective of situating projects according to the character of complexity and followingly applying a suitable approach.

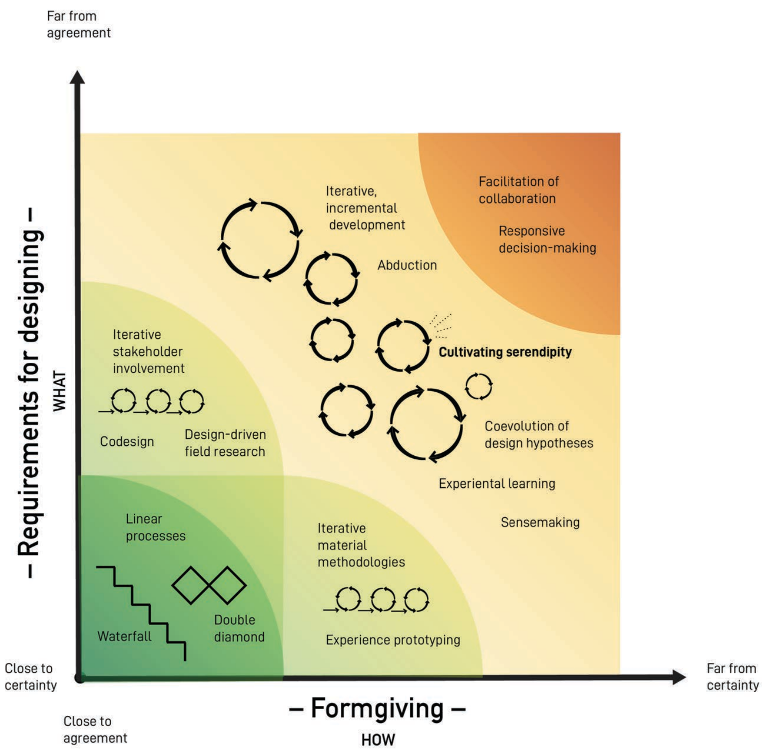



**Figure 39:** Complexity Matrix for Design adapted from Stacey Matrix (Stacey, 1996).

In the following, I will describe the five categories of complexity proposed in the model in the context of design and propose situated approaches.

### Simple

Projects belonging in the simple area represent clear requirements for designing and reliable methods for formgiving to reach the aspired value. We know bot the 'WHAT' and the 'HOW'. Thus, they do not necessarily require an iterative design process. As an example, we can use a refurbishing the design of an existing webpage representing a known type of formgiving and known requirements for design. This way, past experience, data and methods can be applied to plan and predict future outcome of the process and the team can use *technical rational decision-making*. Simple projects often have a repeatable and predictive nature (Dorst, 2015a). I suggest that linear process methodologies, such as the Waterfall method used in software and web development (Royce, 1987), or innovation frameworks, like the two-phased Double Diamond (Design Council, 2005), can be applicable.

**Complicated – Far from Agreement, Close to Certainty**
Projects may have agreement on the feasibility and method of achieving the aspired value based on *formgiving*, but less consensus regarding the *requirements for designing* representing the importance of the value. In other words, we know the 'HOW' at an overall level, but not the 'WHAT'. In this context, a common design challenge arises when we have a particular form of technology or methodology, such as an iPhone mobile app, but there is a lack of consensus on how the app can effectively address a specific problem, like a transport ticket app. This lack of agreement can stem from differing stakeholder perspectives, conflicting research outcomes due to demanding user conditions, and other factors.

I suggest that such projects require a strong sensemaking in balancing and prioritising, negotiations skills to make common decisions, and iterative methodologies where stakeholders are closely involved in the design process to raise the level of agreement. Design methods such as cocreation / codesign (Sanders & Stappers, 2008), and participatory design (Ehn, 2008) are collaborative approaches where users and stakeholders are actively involved. Other methods and techniques that involves users in the process, like participatory observation (DeWalt & DeWalt, 2011), user testing (Dumas & Redish, 1999), card sorting (Morville & Rosenfeld, 2007) and design-driven field research (Lurås & Nordby, 2015) would be important.

**Complicated – Close to Agreement, Far from Certainty**
Projects may have widespread consensus on the aspired value of a project through high agreement about the requirements for designing, but high uncertainty on the underlying concerns of formgiving that will bring about that value. We know the 'WHAT' but not the 'HOW'. When designers are unsure about the links between cause and effect while working with an unestablished type of formgiving (e.g. AR for ship bridges), it is difficult to predict how a certain output will lead to benefit for the requirements for designing and the aspired value. For instance, consider a project where designers aim to create a multi-technology grocery shopping system with diverse interaction methods. While there might be a consensus on user requirements (finding,

scanning, and secure payment), the impact of new technologies remains uncertain. In such scenarios, I suggest that it it's crucial to maintain a cohesive vision for the end goal while fostering flexibility and design experimentation during planning. This approach aligns with Stacey's concept of *judgemental decision-making* in this zone through a rational and analytical process.

Complicated projects can have high agreement of requirements for what the designed should represent, but low certainty in how the formgiving will affect the aspired value. Thus, I suggest that such projects require judgemental decision-making and development based on iterative reframing of the requirements for designing to develop solutions. Uncertainty in formgiving can benefit from using material methodologies to explore the interaction attributes as qualities (e.g.Lim et al. 2007; Nordby, 2010; Wiberg, 2018). Methods and techniques for assessing the exploration's impact on UX and its alignment with requirements for designing can encompass experience prototyping (Buchenau & Suri, 2000) usability testing (Reeves, 2019).

**Complex**
Projects both far from certainty in *formgiving* and agreement in *requirements for designing* characterises projects in the complexity zone. This means that multiple elements and variables connected to both the unagreed 'WHAT' and the uncertain 'HOW' are interconnected and dependent on each other in figuring out both and is thus characterised as intertwined. If we change one element or variable another one can be affected. Complex projects are characterised by numerous risks because they are challenging to frame, to set boundaries within, to plan and make decisions (Dorst, 2015a). The case studies exemplify such projects. AR represents a way of formgiving with high uncertainty in that it is immature, rapidly developing and it has few examples or methods for designers to rely on. A ship's bridge represents an unpredictable and dynamic context resulting in difficulties on agreeing on the requirements for designing. In the zone of complexity, traditional approaches fall short since our previous experiences and knowledge are not applicable.

As described in Chapter 3, I found that such projects require decision-making based on the best guess through hypotheses building (Bang et al., 2012; Dorst, 2011) and situated inquiry. To navigate the uncertainty and unexpectedness found in the complexity zone, I suggest that cultivating serendipity in the design approach has a high potential for integrating successful outcomes into an open a flexible process.

**Chaos**

In the upper right corner, complexity has turned into chaos characterised by minimal uncertainty and agreement. This is often the result of anarchy and breakdown. The chaos zone can be used to represent a complex problem that has not been addressed in a suitable manner and thus developed into chaos which often has the consequences of avoidance by the team members. In chaotic situations, the first step is often sensemaking, which involves trying to understand what is happening. Designers may engage in extensive research, interviews, and observations to make sense of the current situation and identify underlying issues. Further, design approaches should focus on collaboration, and rapid iteration to address minimal agreement and high uncertainty. Designers can use techniques such as facilitation of stakeholder collaboration, experimental prototyping, and agile methodologies to navigate chaos, foster innovation, and adapt to changing circumstances.

The approaches, methods and techniques presented in the complexity matrix for design are suggestions that can be exchanged with the aim of contextualising approaches for concrete purposes. It is important to emphasis, that the model is not about general innovation, but specifically about design.

Applying an approach of mere judgemental decision-making to problems in the complex zone can limit the approach by assumptions and cognitive bias of the designer. Whereas applying an approach of mere political decision-making to complex problems can limit the approach by unforeseen technological deficiencies. Likewise, applying an approach for complex problems to a simple problem will likely result in unnecessary use of time and budget. It can be freeing to recognise and appreciate the realm of unorder, as it allows us to abandon the employment of approaches intended for order in favour of more plausible approaches that works better for unordered contexts (Kurtz & Snowden, 2003).

It is important to emphasise that complexity is not a constant. As described in the Section 2.3, it can be considered a dynamic characterisation because it involves interconnected elements, emergent properties, nonequilibrium states, sensitivity to initial conditions and adaptive behaviours (Funke, 2014). It describes systems or situations that continuously change, evolve, and exhibit unpredictable outcomes.

Likewise, the character of complexity in a design project can and will also alter. Therefore, I suggest that the complexity matrix for design should ideally be used continually in a design process to evaluate if the project, problem, situation, or system has moved towards another zone. Typically, complex projects with poor management or following an insufficient approach have a risk of moving towards the edge of chaos. Conversely, complex projects following a suitable approach have the potential to gradually move towards the complicated or even simple zone, as 'the best guess' develops into more evident theories or foundations.

## 6.3 POTENTIAL RISKS IN CULTIVATING SERENDIPITY

Complex projects are characterised by numerous risks. While cultivating serendipity in an interaction design approach can offer valuable benefits in navigating the complexity zone for design, it is important to be aware of the potential risks and drawbacks.

### 6.3.1 Balancing Openness and Structure

Unexpectedness and change challenge framing, boundary setting, planning, and decision-making in the field of interaction design. This dynamic environment necessitates a rapid heads-up in the design process to recalibrate insights, goals, and approaches. Höök and Löwgren (2021) aptly suggest, 'Interaction designers need to think of their work as interventions into ongoing transformations over which they have only limited control' (p. 34). Acknowledging the lack of control points to the need for new ideals in a successful interaction design process. This implies accepting adaptation of plans and goals in the face of change and uncertainty, as exemplified in the design-driven field research in Publication 2 and in teaching a course in Publication 6. Such adaptability can lead to unpredictable outcomes and make it challenging to meet specific goals or requirements.

To mitigate this risk, I propose designers may need to balance exploration and openness in their approach with the need for structure and control to ensure desired outcomes are achieved. For Concept #2, I described how the defined deliverables of the research projects were structured in an iterative, incremental, and coevolving process. For Concept #4, I discussed how stakeholders were integrated into the iterative assessment in this process. Therefore, I argue that the conceptualisation of how serendipity was cultivated in the case studies described in the results exemplifies a balanced combination between open and structured exploration. This balance ensured that we managed to produce our best-guess deliveries according to each milestone.

### 6.3.2 Time as a Resource

Cultivating serendipity often relies on time as a resource, as seen in Publication 2. However, embracing exploratory activities and experimenting with alternative ideas can extend project timelines and increase costs due to the inherent difficulty to plan accordingly. Striking a balance between time utilisation and project constraints is crucial for maintaining feasibility and efficiency. This challenge is particularly pronounced in projects situated in the simple or complicated zones (2 or 3) of the complexity matrix for design. High agreement on design requirements (Complicated 3) or certainty in formgiving concerns (Complicated 2) or both (simple) can create expectations about project timelines. For example, a project in the simple zone can rely on established requirements and proven design methods, facilitating efficient planning for achieving project goals.

In contrast, complex projects demand an investment of time in exploration. Stacey (1996) emphasises that decision-making in complex projects should rely on intuition, 'identification, development, and selection' and 'outcomes rather than solutions' (p. 47). Intuition is reflected in Concept #1, while 'identification, development and selection' represent the process of coevolution in Concept #2 and 'outcomes rather than solutions' describe the iterative, incremental development of design hypotheses. Restricting exploration by limiting time and budget in complex projects can lead to rushed conclusions, potentially resulting in costly errors. Thus, finding the right balance between time and exploration is crucial for effectively cultivating serendipity in the design process. Here, the complexity matrix for design can function as an important tool to assess this balance.

### 6.3.3 Maintaining Rigour

Cultivating serendipity in the creative process often centres on the integration of unexpected connections and novel ideas. However, this emphasis on the unforeseen may raise concerns – as it could be perceived as distractions, potentially causing designers to overlook critical design considerations such as usability, accessibility, and technical implications. These worries are often shared by stakeholders involved in the project.

Stolterman (2008) argues that methodical rigour and discipline in design can be difficult for professionals from other disciplines to discern.

To address these concerns, designers must remain mindful of striking a balance between the pursuit of serendipitous insights or outcomes and the rigorous evaluation and testing required to meet the broader design requirements. However, as Stolterman (2008) highlights, designerly ways of thinking and acting rely on methods and approaches that prepare them for action rather than guide them in action. For the concepts, I describe how we effectively managed this balance through a guiding approach allowing us to work generatively with design hypotheses, both in the field and in the lab, and by continuously involving stakeholders' evaluation throughout the research process.

### 6.3.4 Effective Communication and Stakeholder Engagement

Effectively communicating the value and rationale behind the approach to cultivating serendipity is a crucial prerequisite, especially when working with team members and stakeholders. Busch (2022) highlights the inhibiting quality of self-censorship in the materialisation of serendipity within collective contexts, emphasising the importance of sharing ideas and insights. Additionally, he suggests that individuals may hinder the cultivation of serendipity by struggling to embrace novel approaches, a phenomenon known as functional fixedness. Overcoming these inhibitors within an organisational context is essential for seizing serendipitous opportunities.

The cognitive process underlying this challenge is detailed in Concept #1 and further explored within team dynamics in Concept #3. Managing stakeholder expectations becomes critical, especially when some stakeholders prefer predictable design processes. Ensuring all parties involved understand and support the prioritisation of serendipity cultivation is essential. As discussed in the concepts, maintaining transparency in the exploration process through continuous delivery of increments and updates that can be tested, evaluated, or implemented by stakeholders proved effective in distributing value throughout the project.

Overall, cultivating serendipity in a pragmatic approach in the complexity zone of design includes risks such as reduced control, time as a resource constraint, potential oversight of critical considerations and the need for effective stakeholder communication. I therefore suggest that designers should carefully assess these risks and tailor the approach to the specific project and its constraints to maximise the benefits while mitigating potential drawbacks.

## 6.4 METHODOLOGICAL LIMITATIONS

### 6.4.1 Reflection on the Methodological Approach

Reading the six appended articles in sequential order reveals the progression of my doctoral research programme, which built upon prior findings. The study began with two parallel collections: the development of the OB design system (Publication 3) and the initial exploratory data collections from design-driven field research (Publication 1 and 2), which informed the subsequent development of the proposed architecture for extending the OB design system to AR (Publication 4), progressed to the development and usability testing of an AR application for icebreaking assistance with intended users (Publication 5) and culminated with the methodical exploration of VRROS in teaching.

The use of case studies focusing on the context of AR on ship bridges may limit the generalizability of the findings to other design domains. Caution should be exercised when applying the results to different contexts. However, context-dependent knowledge is necessary for developing expertise in a specific field (Denzin & Lincoln, 2011). This is particularly important in AR design, where context can be considered part of the material.

### 6.4.2 Data Collection

The findings emerged from various qualitative data collection methods triangulated in a methodological bricolage. The reliance on this approach, while beneficial for addressing multifaceted research questions, may have introduced challenges in maintaining consistency and coherence across different research methods, as suggested by Pratt et al. (2022). The lack of established guidelines may have impacted rigour, increased the risk of unnecessary time and resource consumption, required good triangulation abilities and lowered generalisability. However, for an approach that cultivates serendipity, the acceptance of these risks and disadvantages is a consideration.

### 6.4.3 Data Analysis

The qualitative nature of the analysis and synthesis may have introduced subjectivity and potential biases (Hallihan & Shu, 2013). However, it is important to acknowledge that qualitative research involves interpretation and may be influenced by the researcher's perspective. Being closely connected to a real work-context and facilitating the learning process, the case studies also became a necessary condition for attaining advanced comprehension (Flyvbjerg, 2011).

Due to time constraints, access constraints during COVID-19 restrictions and limited resources, certain aspects of the research were not explored in depth. For example, the study primarily focused on qualitative analysis, which limited the quantitative assessment of specific variables. Expanding the research scope to include quantitative measurements and longitudinal data could provide a more comprehensive understanding of the phenomena under investigation. While these findings await practical application by other design teams and adaptation to other cases, they establish a theoretical foundation for future academic and industry advancements within interaction design.

# 7 CONTRIBUTIONS

In this thesis, I have explored the dynamic landscape of design complexity in interaction design, with a particular focus on the role of serendipity in navigating this complexity. The investigation revealed that serendipity, characterised as the occurrence of unforeseen and advantageous discoveries, is not merely an incidental phenomenon but a strategic component in the design process. This understanding emerged as a pivotal strategy in the case studies, providing a new perspective to unlocking innovative solutions amidst the multifaceted challenges of design complexity. This chapter provides a summary of the main contributions of the thesis. Further, I reflect on potential future research that can build upon the foundations established in this thesis.

## 7.1 TWO DIMENSIONS OF DESIGN COMPLEXITY

In response to the first subsidiary research question (*What are the fundamental aspects of design complexity that interaction designers need to comprehend and address?*), this thesis identified requirements for designing and formgiving concerns as two key dimensions of design complexity. This distinction provides a nuanced understanding of the multifaceted nature of design challenges, particularly in the context of designing AR systems for ship bridges. By contextualising these dimensions in real-world design scenarios, the research contributes to a practical framework for recognising and addressing these aspects of design complexity. This response not only addresses the subsidiary question but also enriches the field of interaction design with a clearer understanding of the varied elements that constitute design complexity.

**Requirements for Designing**
The requirements for designing represent the prerequisites, conditions, specifications or rules a designer needs to consider (see Table 4 in Section 4.2)

**Formgiving Concerns**
The formgiving concerns entail aesthetic, structural and material considerations, shaping an intended UX through their harmonious integration (see Table 5 in Section 4.3).

The articulation of two dimensions for complexity in interaction design is useful for navigating projects in practice because they distinguish the comprehension of the problem from the materialisation of the solution. Moreover, by conceptualising complexity into the two separate dimensions, it becomes clearer how they are intertwined. Together, the two dimensions constitute a new understanding of key requirements for designing and concerns for formgiving within interaction design. To overcome these challenges, we employed a pragmatic material-oriented approach, where complexity's inherent uncertainty and unexpectedness was navigated by cultivating serendipity.

## 7.2 MECHANISMS AND QUALITIES FOR CULTIVATING SERENDIPITY

Here, I address the second subsidiary research question: In what ways can serendipity be deliberately nurtured and integrated into the interaction design process to enhance sensemaking and creative outcomes? This thesis underscores the significance of serendipity in design complexity. It posits that unexpectedness and chance encounters, often overlooked in conventional design processes, are pivotal in navigating complex design scenarios. This strategic approach is grounded in a theoretical exploration that interweaves the unpredictable aspects of design projects with serendipitous discoveries, proposing a paradigm shift in how designers approach complexity. The research question addresses qualities and mechanisms necessary for cultivating serendipity within the design process. I respond by proposing four key concepts, each describing a unique perspective on cultivating serendipity in interaction design.

**Concept #1: Cultivating a Serendipitous Mind**
I provide a cognitive perspective on how interaction designers perceive and make decisions in navigating design complexity. In an incomplete encounter with unfamiliarity, unexpectedness, and change, they perceive serendipitous cues. Here, I explore how they can manage their attention towards serendipitous cues, recognise serendipitous patterns, seize serendipitous opportunities, and create conductive conditions for serendipity. These models contribute to an understanding of making sense of complexity while highlighting the role of serendipity's potentiality throughout the process by defining four important aspects for its materialisation. Further, I propose several qualities supporting these processes that can be emphasised and developed. The conceptualisation of cultivating serendipity as a

cognitive process with its associated qualities represents serendipitous sensemaking as a new ideal for how interaction designers navigate design complexity.

**Concept #2: Cultivating Serendipity in the Design Process**
Here, I describe how the process can be designed as coevolving iterative increments to facilitate the rapid heads-up in the design team – where change and unexpected aspects can be integrated, increasing the chance for incorporating serendipity patterns. I emphasise research integration mechanisms for serendipity, such as employing abductive reasoning and the development of design hypotheses on practical and principal levels, as essential for handling design complexity. This concept emphasises the value of adapting incremental, iterative methodologies to design and the coevolution of design hypotheses as new ideals for designing processes to navigate complex design ecologies.

**Concept #3: Cultivating Serendipity in the Team**
For this concept, I describe how design complexity can be navigated on a team level by analysing the case studies from a team perspective to identify values of the approach. I compare and adapt these values with Agile values, which is a methodology suggested to be employed in the complexity zone (Wingo & Tanik, 2015). Based on how the adapted values formed the teamwork, I elucidate mechanisms employed for cultivating serendipity. Here, I emphasise values of self- and team efficacy, together with organic collaboration for the benefit of prestructured plans. This concept underlines the importance of team dynamics and collaborative efforts in navigating complexity and integrating serendipitous discoveries into the design process.

**Concept #4: The Generative Role of Tools**
Here, I focus on how we engage with interaction materials through design tools and how they can hold a generative role, allowing a nuanced and pragmatic exploration of design complexity. A hands-on engagement with the materials of the situation can guide not only the problem solution but, more importantly, the problem definition. I emphasise several mechanisms and catalysts for cultivating serendipity through our extended capabilities through tools. As ideal, this concept introduces an emphasis on our embodied exploration of the situation through materials, where tools are not seen as layers between us and the world but rather as an extension of our acting and thinking. It examines how various tools and technologies can facilitate the

discovery of unexpected insights and ideas, thereby contributing to the serendipitous design process.

These concepts provide a conceptual framework for understanding how serendipity can be harnessed in the design process, contributing to the discourse on designing in uncertain and dynamic environments. Significantly, they focus on serendipity as a means rather than a goal for the design process. By elucidating how mechanisms and qualities can be employed individually and collectively, through processes and tools, this framework allows designers to view unexpectedness as a space for potentiality and the materialisation of valuable outcomes.

Drawing on the analysis of the six publications, these concepts highlight the importance of pragmatism in interaction design through hands-on engagement with design exemplars for developing a conceptual understanding of complex systems. This approach provides a dialectic perspective on problem-solving, acknowledging the role of chance in early form exploration.

## 7.3 THE INTERPLAY OF COMPLEXITY AND SERENDIPITY

Building upon the subsidiary research questions, I will finally address the contributions of the main research question: *How can interaction designers develop a pragmatic approach to navigate design complexity by cultivating serendipity?* The core contribution of this thesis is the conceptualisation of serendipity as a strategic tool within the design process addressing design complexity. This strategic cultivation of serendipity directly addresses the main research question by demonstrating how serendipity can be deliberately nurtured and integrated into various facets of the design process, aiding designers in navigating the intricate challenges of design complexity. Four key concepts – cognitive perspective, process integration, team dynamics and tool utilisation – collectively form a comprehensive framework, illustrating how serendipity can be into the design process. This approach not only answers the main research question but also offers practical insights for designers to accommodate the potentiality of serendipity in unpredictability and unexpectedness and leverage it to materialise serendipitous innovation and creativity in their work.

The theoretical framework of this thesis builds on my notion of the overlap of *unexpectedness and chance* between design complexity and serendipity. Navigating design complexity by cultivating serendipity, I have explored how pragmatism can be understood in interaction design. To bring about such an understanding, it was crucial to employ a reflective, hands-on exploration of design complexity. I did this through practice-led form of research by and into design, using case studies as a research strategy. Within the case studies, I employed a methodological bricolage consisting of methods and techniques such as experience prototyping, sketching and design-driven field research. This methodology laid the groundwork for investigating the dimensions of design complexity and the cultivation of serendipity in the design process by analysing and synthesising. Further, it responded to the research gaps of design precedents, design frameworks and methodologies for designing for AR.

## 7.4 RESEARCH TRANSFERABILITY

This research introduces a conceptualisation of both design complexity and the cultivation of serendipity corresponding with each other, providing valuable insights and practical guidance for designers and researchers. The focus on enhancing safety and efficiency in ship bridge design aligns with emerging trends in both interaction design and the maritime sector (Gernez et al., 2020). The disseminated design guidelines benefit interaction designers and related fields in the maritime domain. The conceptual frameworks, methodologies and design contributions advance interaction design and offer insights for future research. The research's impact is evident in its substantial engagement and citations within the academic community, underlining its significance.

This research's insights on serendipity extend to complex domains such as AR systems for ship bridges. Embracing serendipity helps designers navigate complexity and find innovative solutions resonating beyond design into broader creative discussions (Thompson & Copeland, 2023). Its inclusion in *The Art of Serendipity* (Copeland, 2022) highlights its cross-disciplinary relevance. Additionally, the OICL's serendipitous research culture and process design enhances relevance through customer collaboration and adaptability. Involvement of industrial partners and end users ensures alignment with real-world needs and timely responses to challenges, reinforcing the research's relevance in design and the maritime sector.

## 7.5 FUTURE DIRECTIONS

The contributions of this thesis have significant implications for the field of interaction design. By providing a detailed framework for understanding and navigating design complexity through the lens of serendipity, it opens new avenues for creative exploration and problem-solving. The research not only addresses the initial research questions but also lays the groundwork for future investigations in several key areas:

**Application to Diverse Design Contexts**
This involves extending the application of the complexity matrix for design and the principles of serendipity to a broader range of design contexts to validate and refine their utility. Such efforts could, for example, be to explore the dimension of design complexity as it applies to other dynamic and safety-critical environments, such as hospitals, representing similar complexities through integration with existing multivendor systems requiring safe and efficient navigation, SA, interaction and collaboration, emergency, operation, and training.

**Cognitive Processes in Serendipity**
Further investigation into the cognitive processes associated with recognising and leveraging serendipitous opportunities in design are needed.

**Development of New Tools and Methodologies**
The research calls for the creation and evaluation of new design tools and methodologies that embody the principles of serendipity, especially for use in complex and chaotic scenarios.

**Understanding the Impact of Team Dynamics**
In-depth research on how team dynamics, organisational structures and cultural factors contribute to or hinder the cultivation of serendipity in design processes should be conducted.

**Exploring Cross-Disciplinary Applications**
The study of serendipity should be expanded beyond interaction design to other creative and scientific fields to enrich the current understanding of its universal applicability and impact.

In conclusion, this thesis repositions serendipity from a ‘slippery’, chance-based phenomenon to a central, strategic element in the toolkit of interaction designers. By embracing unpredictability and fostering a mindset attuned to serendipitous discoveries, designers can navigate the ever-changing and challenging landscape of interaction design more adeptly. This perspective shift not only answers the initial research questions but also promises a richer, more dynamic future for the field of design.

## 7.6 IMPACT, SIGNIFICANCE AND CLOSING REMARKS

My PhD study began six years ago, and I encountered various significant life events that influenced the duration of my research. These events included moments of profound joy and responsibility as my family expanded, as well as unexpected challenges and global disruptions (e.g. COVID-19). These experiences became an integral part of my doctoral journey, shaping my resilience and adaptability and, most importantly, providing me with an extended perspective on the development of the OICL research group, to which I belong.

Over the past decade, the OICL has undergone remarkable growth in its research achievement. When I joined in 2017, the group had already laid a strong foundation in maritime sector research through projects such as the Ulstein Bridge Concept, the Ulstein Bridge Vision, MIX, Distribute, Holographic and ONSITE. As I became part of the group, the projects OpenBridge and SEDNA, building upon previous work, gained substantial attention and engagement from the maritime industry. Through the development of the open-source OB design system, the OICL has fostered a diverse network of academic and industrial collaborators who actively contribute by sharing their needs, evaluating designs, providing domain expertise and, most importantly, implementing designs in real-world contexts.


**Figure 40:** OpenBridge partners, including representatives from industry, academia, and government, collaborating on the latest research project, OpenZero. (Illustration: OICL)

Consequently, the OICL has evolved into a unique academic institution with a strong industry focus, offering a comprehensive design system tailored to the maritime domain. Currently, we have 40 government, industrial and research partners in OB-related research projects (Figure 40), currently boasting a global user base. The growing adoption of the OB design system by our industrial partners has played a pivotal role in evaluating its practical value, as evidenced by its successful implementation at Brunvoll (Figure 41). This impact on the industry has led to several additional research projects (including OpenVR, OpenAR, OpenRemote and OpenZero), further expanding the reach and application of our work. Collectively, the OICL has established design-driven research projects of nearly 100 million Norwegian kroner, marking a significant influence on the sector.


**Figure 41:** OpenBridge partners for industry, academia, and government. (Illustration: OICL)

In reflection, the concept of cultivating serendipity described in this thesis aligns well with the spirit of our research group. Through hands-on exploration of design complexity and the crafting of innovative solutions, the OICL has demonstrated how mechanisms and qualities for nurturing serendipity naturally emerge and contribute to innovative outcomes. While these outcomes result from a combination of factors, I suggest it is likely that the cultivation of serendipity plays a central role.

# 8 CONCLUSIONS

This thesis has explored the opportunities for enhancing design approaches to navigate design complexity by cultivating serendipity. I have used practice-led, case-driven research by and into design to approach design complexity within real-world settings. To contextualise this study, I have investigated the premises and possibilities for designing AR UIs for applications and systems on ship bridges specifically. The primary emphasis has been dual: articulating *requirements for designing* and *formgiving concerns* for interaction design of AR UIs into concrete design frameworks and exemplars and conceptualising the cultivation of serendipity – both within the field of interaction design for the maritime domain. The overall objective of this research has been to develop a conceptual understanding of design complexity by exploring the cultivation of serendipity as a strategy for navigating this.

Key contributions from this thesis include the following:

**Pragmatic Practice-Led Research**
Pragmatism in interaction design can be understood as a hands-on engagement with materials of the situation. Addressing this through the examination of real-world complexity is key. Therefore, to manage the uncertainty, change and unexpectedness inherent in design complexity in a pragmatic manner, designing processes as iterative, incremental, and coevolving can enhance the focus on exploring the situation from a tangible perspective.

**Practical Frameworks for Categorising and Navigating Design Complexity in Interaction Design**
This thesis has proposed a practical framework for categorising and navigating design complexity by developing practical examples of requirements for designing and formgiving concerns tailored to the design of AR UIs for ship bridges. However, the adoption of such requirements and concerns by interaction designers requires a comprehensive adaptation to the real-world context they are facing, such as interaction material, domain, stakeholders, users, operations, and regulations. Successful integration necessitates a comprehensive understanding and exploration of the materials of their situation.

The complexity matrix for design (Figure 39) provides a model for assessing forms of complexity within a project and exemplifies approaches that correspond with the form of decision-making found in the five zones. This visual representation of complexity as a landscape with different characters facilitates a simplified, yet nuanced, tool for designers to comprehend the causes and effects of their approaches.

### Cultivating Serendipity in Design

Consciously cultivating serendipity within the design process presents a largely untapped potential. This ongoing perceptual process of cultivation can be categorised into four key stages: being attentive to serendipitous cues, recognising serendipitous patterns, seizing serendipitous opportunities, and creating conducive conditions for serendipity. Employing lens models to depict how designers perceive and navigate serendipitous cues in their surroundings, this thesis offers a cognitive perspective on comprehending various aspects of serendipity within a design case study. Furthermore, serendipity cultivation can be facilitated by the enhancement of mechanisms for resource integration and collaboration and by adopting certain qualities and values as strategic approaches.

### Design Precedents and Design Frameworks for the Design of AR for Ship Bridges

The absence of design frameworks and design precedents for the development of AR for ship bridges adds to the design complexity for interaction designers. This complexity is amplified by the rapid advancement of technology and inherent challenges of designing for high-risk domains. As a result, there is a notable lack of research, regulations, and practical examples to guide designers in this work. The publications in this thesis aim to address this gap by analysing and consolidating the best possible insights into requirements for designing and formgiving concerns. These insights are then translated into design exemplars and design frameworks, offering a valuable contribution to the development of AR for ship bridges.

### Methodological Perspectives for the Design of AR for Ship Bridges

Exploring the requirements for designing and the formgiving concerns for the design of AR UIs for ship bridges requires novel methods and approaches to meet the new ideals for interaction design. The contextual environment plays a crucial role in exploring AR as an interaction material. Therefore, context-oriented methods and techniques allowing designers to immerse in and explore the physical, spatial, and temporal aspects of the environment, such as design-driven field research for AR and VRROS, are central.

Navigating design complexity in interaction design relies on a conceptual understanding of its dimensions, their interconnectedness and how to approach the complexity terrain in way that harnesses the potential within the unexpectedness. The data collection, design exemplars and conceptual frameworks developed in this thesis explore new terrains within interaction design. Hence, I aimed to adopt and further develop theoretical models from the fields of psychology and organisational research to facilitate integration and adoption by designers. While the thesis primarily focused on the articulation of design complexity within the maritime domain and by AR specifically, it underscores the need for a generalised understanding of design complexity across domains and interaction materials to recognise the value of cultivating serendipity. Conscious facilitation of mechanisms for cultivating serendipity in the many facets of the design process can contribute to richer design outcomes, inclusive values, reflective learning, and adaptive planning and ultimately enhance the collaborative synergies for both team members and stakeholde

# REFERENCES

Abidin, S. Z., Sigurjónsson, J., Liem, A., & Keitsch, M. (2008, September 4). *On the role of formgiving in design*. In Proceedings of the 10th International Conference on Engineering and Product Design Education - New Perspectives in Design Education (Vol. DS46-1, pp. 365-370). DOI: 10.13140/2.1.1922.4649.

Agarwal, N. K. (2015). Towards a definition of serendipity in information behaviour. *Information Research*, *20*(3). https://eric.ed.gov/?id=EJ1077837

Åkerström, M. (2013). Curiosity and serendipity in qualitative research. *Qualitative Sociology Review*, *9*(2), Article 2. https://doi.org/10.18778/1733-8077.09.2.02

Allianz Global Corporate & Specialty. (2021). *Safety and shipping review 2021: An annual review of trends and developments in shipping losses and safety.*

Alsaqqa, S., Sawalha, S., & Abdel-Nabi, H. (2020). Agile software development: Methodologies and trends. *International Journal of Interactive Mobile Technologies*, *14*(11), 246–270. https://doi.org/10.3991/ijim.v14i11.13269

Alshamrani, A., & Bahattab, A. (2015). A comparison between three SDLC models waterfall model, spiral model, and incremental/iterative model. *International Journal of Computer Science Issues*, *12*(1), 106–111.

André, P. A., Schraefel, M. C., Teevan, J., & Dumais, S. (2009). Discovery is never by chance: Designing for (un)serendipity. In *Proceedings of the 2016 ACM conference on designing interactive* systems. In Proceedings of the Seventh ACM Conference on Creativity and Cognition (pp. 305–314). Association for Computing Machinery. DOI: 10.1145/1640233.1640279.

Anwar, R., Abidin, S. Z., & Hassan, O. H. (2015). A pattern in formgiving design: Giving priority to a principle solution in industrial design situation. In M. Gen, K. J. Kim, X. Huang, & Y. Hiroshi (Eds.), *Industrial engineering, management science and applications 2015* (pp. 331–340). Springer. https://doi.org/10.1007/978-3-662-47200-2_35

Apple Developer. (2023). *Apple design: Augmented reality*. https://developer.apple.com/design/human-interface-guidelines/augmented-reality

Ash, N., Woodward, M., & Thompson, S. (2023). The happy accident: Post-anthropocentric understandings of serendipity in making processes. *Craft Research*, 14(1), 101-115. https://doi.org/10.1386/crre_00096_1

Ashtari, N., Bunt, A., McGrenere, J., Nebeling, M., & Chilana, P. K. (2020). Creating augmented and virtual reality applications: Current practices, challenges, and opportunities. In *Proceedings of the 2020 CHI conference on human factors in computing systems* (pp. 1–13). https://doi.org/10.1145/3313831.3376722

Austin, J. H. (2003). *Chase, chance, and creativity: The lucky art of novelty*. MIT Press.

Austin, R. D., Devin, L., & Sullivan, E. E. (2012). Accidental innovation: Supporting valuable unpredictability in the creative process. *Organization Science*, *23*(5), 1505–1522. https://doi.org/10.1287/orsc.1110.0681

Aylward, K., Dahlman, J., Nordby, K., & Lundh, M. (2021). Using operational scenarios in a virtual reality enhanced design process. *Education Sciences*, *11*(8), Article 8. https://doi.org/10.3390/educsci11080448

Back, K., Beedle, M., van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Jefferies, R., Kern, J., Marick, B., Martin, R. C., Mellor, S., Schwaber, K., Sutherland, J., & Thomas, D. (2001). *Manifesto for agile software development*. Agile Manifesto. http://agilemanifesto.org/
Baldauf, M., & Procee, S. (2014). *Augmented reality in ships bridge operation*. In Proceedings of the ISIS 2014 – International Symposium Information on Ships, Berlin, Germany, 27–28 September 2014. Retrieved from https://www.researchgate.net/publication/273057248_Augmented_Reality_in_Ships_Bridge_Operation
Bang, A. L., Krogh, P., Ludvigsen, M., & Markussen, T. (2012). The role of hypothesis in constructive design research. In *Proceedings of The Art of research IV* (pp.1–11). Retrieved from https://adk.elsevierpure.com/en/publications/the-role-of-hypothesis-in-constructive-design-research
Bardone, E. (2013). *Seeking chances: From biased rationality to distributed cognition*.
Bardone, E., & Secchi, D. (2017). Inquisitiveness: Distributing rational thinking. *Team Performance Management*, 23(1/2), 66–81. https://doi.org/10.1108/TPM-10-2015-0044
Bass, J. M., Beecham, S., & Noll, J. (2018). Experience of industry case studies: A comparison of multi-case and embedded case study methods. In *Proceedings of the 6th International Workshop on Conducting Empirical Studies in Industry* (pp. 13–20). https://doi.org/10.1145/3193965.3193967
Beck, C. (2019, September 25). Design systems create bad designers. *Modus*. https://modus.medium.com/suburban-tract-housing-and-the-death-of-craftsmanship-a-critique-of-digital-design-systems-34c0fc1e106f
Beghetto, R. A. (2019). Structured uncertainty: how creativity thrives under constraints and uncertainty. In C. A. Mullen (Ed.), *Creativity under duress in education? Resistive theories, practices, and actions* (pp. 27–40). Springer International Publishing. https://doi.org/10.1007/978-3-319-90272-2_2
Benedict, K., Kirchhoff, M., Gluch, M., Fischer, S., Schaub, M., & Baldauf, M. (2016). Simulation-augmented methods for safe and efficient manoeuvres in harbour areas. TransNav, 10(2), 193–201. https://doi.org/10.12716/1001.10.02.02
Benyon, D. (2019). *Designing user experience*. Pearson UK.
Bertelsen, O. W., & Pold, S. (2004). Criticism as an approach to interface aesthetics. In *Proceedings of the third Nordic conference on human-computer interaction* (pp. 23–32). https://doi.org/10.1145/1028014.1028018
Beyer, H., & Holtzblatt, K. (1997). *Contextual design: Defining customer-centered systems*. Morgan Kaufmann.
Binder, T., & Redström, J. (2008). Exemplary Design Research. In K. Friedman, T. Love, E. Côrte-Real, & C. Rust (Eds.), *Wonderground - DRS International Conference 2006*, November 1-4, Lisbon, Portugal. Retrieved from https://dl.designresearchsociety.org/drs-conference-papers/drs2006/researchpapers/51
Birkinshaw, J., Gudka, M., & D'Amato, V. (2021). The blinkered boss: How has managerial behavior changed with the shift to virtual working? *California Management Review*, *63*(4), Article 4.
Bjarke Ingels Group. (2020). *Formgiving: An architectural future history*. Taschen. https://www.norli.no/boker/hobby-og-fritid/kunst-og-kultur/kunstnere-og-kunsthistorie/big-formgiving-an-architectural-future-history
Björneborn, L. (2017). Three key affordances for serendipity: Toward a framework connecting environmental and personal factors in serendipitous encounters.

*Journal of Documentation*, *73*(5), 1053–1081. https://doi.org/10.1108/JD-07-2016-0097
Blandford, A., Faisal, S., & Attfield, S. (2014). Conceptual design for sensemaking. In *Handbook of human centric visualization* (pp. 253–283). Springer: New York, NY, USA. https://doi.org/10.1007/978-1-4614-7485-2_10
Blevis, E., Lim, Y. K., & Stolterman, E. (2006). Regarding software as a material of design. *Wonderground – DRS International Conference 2006*. Design Research Society, Lisbon, Portugal.
Body, J., & Terrey, N. (2019). *Design for a better future: A guide to designing in complex systems*. Routledge.
Bogers, M., Chesbrough, H., Heaton, S., & Teece, D. J. (2019). Strategic management of open innovation: A dynamic capabilities perspective. *California Management Review*, *62*(1), 77–94. https://doi.org/10.1177/0008125619885150
Boll, S., Palanque, P., Mirnig, A. G., Cauchard, J., Lützhöft, M. H., & Feary, M. S. (2020). Designing safety critical interactions: Hunting down human error. In *Extended abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–7). https://doi.org/10.1145/3334480.3375148
Bowen, S., Durrant, A., Nissen, B., Bowers, J., & Wright, P. (2016). The value of designers' creative practice within complex collaborations. *Design Studies*, *46*, 174–198. https://doi.org/10.1016/j.destud.2016.06.001
Bressa, N., Korsgaard, H., Tabard, A., Houben, S., & Vermeulen, J. (2022). What's the situation with situated visualization? A survey and perspectives on situatedness. *IEEE Transactions on Visualization and Computer Graphics*, *28*(1), 107–117. https://doi.org/10.1109/TVCG.2021.3114835
Brinkmann, M. (2016). Repetition and transformation in learning: A hermeneutic and phenomenological view on transformative learning experiences. In A. Laros, T. Fuhr, & E. W. Taylor (Eds.), *Transformative learning meets* bildung (pp. 73–84). Sense Publisher.
Brinkmann, S. (2013). *John Dewey: Science for a changing world*. AldineTransaction.
Brinkmann, S. (2014). Doing without data. *Qualitative Inquiry*, *20*, 720–725. https://doi.org/10.1177/1077800414530254
Brinkmann, S. (2020). Conversational knowledge and gifts of chance: On the state of the method. *International Journal of Qualitative Methods*, *19*. https://doi.org/10.1177/1609406920939426
Brunswik, E. (1935). *Experimentelle psychologie in demonstrationen* [Experimental psychology in demonstrations]. Springer. https://doi.org/10.1007/978-3-7091-9901-5
Brunswik, E. (1943). Organismic achievement and environmental probability. *Psychological Review*, *50*(3), 255–272. https://doi.org/10.1037/h0060889
Brunswik, E. (1952). The conceptual framework of psychology. University of Chicago Press, Chicago.
Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues*, *8*(2), 5–21. https://doi.org/10.2307/1511637
Buchanan, R. (2019). Systems thinking and design thinking: The search for principles in the world we are making. *She Ji*, *5*(2), 85–104. https://doi.org/10.1016/j.sheji.2019.04.001
Buchenau, M., & Suri, J. F. (2000). Experience prototyping. In *Proceedings of the 3rd conference on designing interactive systems: Processes, practices, methods, and techniques* (pp. 424–433). https://doi.org/10.1145/347642.347802

Busch, C. (2020). *The serendipity mindset: The art and science of creating good luck*. Penguin Life.

Busch, C. (2022a). *Connect the dots: The art and science of creating good luck*. Penguin Life.

Busch, C. (2022b). Towards a theory of serendipity: A systematic review and conceptualization. *Journal of Management Studies*. Advance online publication. https://doi.org/10.1111/joms.12890

Busch, C., & Barkema, H. (2022a). Align or perish: Social enterprise network orchestration in sub-Saharan Africa. *Journal of Business Venturing*, *37*(2). https://ideas.repec.org//a/eee/jbvent/v37y2022i2s0883902621000975.html

Busch, C., & Barkema, H. (2022b). Planned luck: How incubators can facilitate serendipity for nascent entrepreneurs through fostering network embeddedness. *Entrepreneurship Theory and Practice*, *46*(4), 884–919. https://doi.org/10.1177/1042258720915798

Busch, C., & Grimes, M. (2023). Eureka!: Improving the effects of artificial intelligence on serendipitous innovation. *Academy of Management Proceedings*, *2023(1)*. https://doi.org/10.5465/AMPROC.2023.11339abstract

Buxton, B. (2007). *Sketching user experiences: Getting the design right and the right design*. Morgan Kaufmann.

Cajander, Å., Larusdottir, M., & Geiser, J. L. (2022). UX professionals' learning and usage of UX methods in agile. *Information and Software Technology*, *151*, Article 107005. https://doi.org/10.1016/j.infsof.2022.107005

Candy, L. (2006). *Practice based research: A guide* (CCS Report No. 2006-V1.0 November). University of Technology.

Chiapello, L., & Bousbaci, R. (2022). It's complicated: Dewey, Schön and reflection-in-action. In D. Lockton, S. Lenzi, P. Hekkert, A. Oak, J. Sádaba, & P. Lloyd (Eds.), *DRS2022*: Bilbao, 25 June - 3 July. Bilbao, Spain. https://doi.org/10.21606/drs.2022.349

Claisse, C., Dulake, N., & Petrelli, D. (2019). Design synthesis: An act of Research through Design. In *Proceedings of the 4th Biennial Research Through Design Conference*, 19-22 March 2019, Delft and Rotterdam, The Netherlands (pp. 1-16). https://doi.org/10.6084/m9.figshare.7855826.v1

Clancey, W. J. (1985). Heuristic classification. *Artificial Intelligence*, *27*(3), 289–350. https://doi.org/10.1016/0004-3702(85)90016-5

Conboy, K., Gleasure, R., & Cullina, E. (2015). Agile design science research. In B. Donnellan, M. Helfert, J. Kenneally, D. VanderMeer, M. Rothenberger, & R. Winter (Eds.), *New horizons in design science: Broadening the research agenda* (pp. 168–180). Springer International Publishing. https://doi.org/10.1007/978-3-319-18714-3_11

Cooke-Davies, T., Cicmil, S., Crawford, L., & Richardson, K. (2007). We're not in Kansas anymore, Toto: Mapping the strange landscape of complexity theory, and its relationship to project management. *Project Management Journal*, *38*(2), 50–61. https://doi.org/10.1177/875697280703800206

Cooper, A., Reimann, R., Cronin, D., & Noessel, C. (2014). *About face: The essentials of interaction design* (4th ed.). Wiley.

Copeland, S. (2022). Metis and the art of serendipity. In W. Ross & S. Copeland (Eds.), *The art of serendipity* (pp. 41–73). Palgrave Macmillan.

Cordon, J. R., Mestre, J. M., & Walliser, J. (2017). Human factors in seafaring: The role of situation awareness. *Safety Science*, *93*, 256–265. https://doi.org/10.1016/j.ssci.2016.12.018
Coyne, R. (2005). Wicked problems revisited. *Design Studies*, *26*(1), 5–17. https://doi.org/10.1016/j.destud.2004.06.005
Cross, N. (1997). Descriptive models of creative design: Application to an example. *Design Studies*, *18*(4), 427–440. https://doi.org/10.1016/S0142-694X(97)00010-0
Cross, N. (2001). Designerly ways of knowing: Design discipline versus design science. *Design Studies*, *17*(3), 49–55. https://doi.org/10.1016/0142-694X(82)90040-0
Cross, N. (2003). The expertise of exceptional designers. In N. Cross & E. Edmonds (Eds.), Creativity and Cognition Press, University of Technology.
Cross, N. (2006). *Designerly ways of knowing* (2006 ed.). Springer.
Cross, N. (2023). *Design thinking: Understanding how designers think and work*. Bloomsbury Publishing.
Csikszentmihalyi, M. (2013). *Creativity: Flow and the psychology of discovery and invention.* Harper Perennial.
Culkin, J. M. (1967, March 18). A schoolman's guide to Marshall McLuhan. *The Saturday Review*, 51–53.
Cunha, M. P. e., & Berti, M. (2023). Serendipity in management and organization studies. In S. Copeland, W. Ross, & M. Sand (Eds.), *Serendipity science: An emerging field and its methods* (pp. 49–67). Springer.
Cunha, M. P. e., Clegg, S. R., & Mendonça, S. (2010). On serendipity and organizing. *European Management Journal*, *28*(5), 319–330.
Cunha, M. P. e., Rego, A., Clegg, S., & Lindsay, G. (2015). The dialectics of serendipity. *European Management Journal*, *33*(1), 9–18.
Daalhuizen, J. (2014). *Method usage in design – How methods function as mental tools for designers* [Unpublished doctoral dissertation]. Delft University of Technology.
Daalhuizen, J., Timmer, R., van der Welie, M., & Gardien, P. (2019). An architecture of design doing: A framework for capturing the ever-evolving practice of design to drive organizational learning. *International Journal of Design*, *13*(1). http://www.ijdesign.org/index.php/IJDesign/article/view/2814/847
Dalsgaard, P. (2014). Pragmatism and design thinking. *International Journal of Design*, *8*, 143–155.
Davis, M. (2008). Why do we need doctoral study in design? *International Journal of Design*, *2*(3). http://www.ijdesign.org/index.php/IJDesign/article/view/481/223
Debnath, L., & Basu, K. (2015). A short history of probability theory and its applications. *International Journal of Mathematical Education in Science and Technology*, *46*(1), 13–39. https://doi.org/10.1080/0020739X.2014.936975
Melo, R. M. C. (2018). On *Serendipity in the Digital Medium: Towards a Framework for Valuable Unpredictability in Interaction Design* (Publication No. 10972947). Universidade do Porto (Portugal). ProQuest Dissertations Publishing.
Denrell, J. (2003). Vicarious learning, undersampling of failure, and the myths of management. *Organization Science*, *14*(3), 227–243. https://doi.org/10.1287/orsc.14.3.227.15164
Denzin, N. K., & Lincoln, Y. S. (Eds.). (2011). *The SAGE handbook of qualitative research* (4th ed.). SAGE Publications.

Design Council. (2005). *Framework for innovation: Design Council's evolved Double Diamond*. https://www.designcouncil.org.uk/our-work/skills-learning/tools-frameworks/framework-for-innovation-design-councils-evolved-double-diamond/

Detienne, M., & Vernant, J.-P. (1991). *Cunning intelligence in Greek culture and society*. University of Chicago Press.

Deutsch, D. (1998). *The fabric of reality: The science of parallel universes—And its implications* (Illustrated ed.). Penguin Books.

DeWalt, K. M., & DeWalt, B. R. (2011). *Participant observation: A guide for fieldworkers*. Rowman Altamira.

Dewey, J. (1925). *Experience and nature* (Enlarged, Revised ed.). Dover Publications.

Dewey, J. (1938a). *Experience and education*. New York: Macmillian Company.

Dewey, J. (1938b). *Logic—The theory of inquiry*. Saerchinger Press.

Dickson, G., & Stolterman, E. (2016). Why design method development is not always carried out as user-centered design. In *Proceedings of the 2016 CHI conference on human factors in computing systems* (pp. 4056–4060). https://doi.org/10.1145/2858036.2858324

Dixon, B. S. (2020). *Dewey and design: A pragmatist perspective for design research*. Springer.

Dodevska, Z., & Mihic, M. (2014). Theory of complexity and innovation projects. In *Proceeding of the XIV International Symposium SymOrg 2014*, New Business Models and Sustainable Competitiveness (pp. 1460–1468). Zlatibor, Serbia.

Dorst, K. (2006). Design problems and design paradoxes. *Design Issues*, *22*(3), 4–17. https://doi.org/10.1162/desi.2006.22.3.4

Dorst, K. (2011). The core of "design thinking" and its application. *Design Studies*, *32*(6), 521–532. https://doi.org/10.1016/j.destud.2011.07.006

Dorst, K. (2015a). Frame creation and design in the expanded field. *She Ji*, *1*(1), 22–33. https://doi.org/10.1016/j.sheji.2015.07.003

Dorst, K. (2015b). *Frame innovation: Create new thinking by design*. MIT Press. https://doi.org/10.7551/mitpress/10096.001.0001

Douven, I. (2021). Abduction. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Summer 2021 ed.). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/sum2021/entries/abduction/

Dumas, J. S., & Redish, J. C. (1999). *A practical guide to usability testing* (Revised ed.). Intellect.

Dunbar, K. N., & Fugelsang, J. A. (2005). Causal Thinking in Science: How Scientists and Students Interpret the Unexpected. In M. E. Gorman, R. D. Tweney, D. C. Gooding, & A. P. Kincannon (Eds.), *Scientific and Technological Thinking* (pp. 57–79). Lawrence Erlbaum Associates Publishers.

Edelson, D. C. (2002). Design research: What we learn when we engage in design. *Journal of the Learning Sciences*, *11*(1), 105–121. https://doi.org/10.1207/S15327809JLS1101_4

Edmondson, A. C. (2018). *The fearless organization: Creating psychological safety in the workplace for learning, innovation, and growth*. Wiley.

Edmondson, A. C., & Mortensen, M. (2021, April 19). What psychological safety looks like in a hybrid workplace. *Harvard Business Review*. https://hbr.org/2021/04/what-psychological-safety-looks-like-in-a-hybrid-workplace

Ehn, P. (2008). *Participation in design things*. *Proceedings of the Tenth Anniversary Conference on Participatory Design, PDC 2008*, Bloomington, Indiana, USA, October 1–4, 2008 (pp. 92–101). https://doi.org/10.1145/1795234.1795248

Eikenes, J. O. H. (2019, June). How to create your own HoloLens sun screen. *Medium*. https://medium.com/ocean-industries-concept-lab/how-to-create-your-own-hololens-sun-screen-68c466071a01

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, *37*(1), 32–64. https://doi.org/10.1518/001872095779049543

Endsley, T., Sprehn, K., Brill, R., Ryan, K., Vincent, E., & Martin, J. (2017). Augmented reality design heuristics: Designing for dynamic interactions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *61*, 2100–2104. https://doi.org/10.1177/1541931213602007

Erdelez, S. (2004). Investigation of information encountering in the controlled research environment. *Information Processing and Managment*, *40*, 1013–1025. https://doi.org/10.1016/j.ipm.2004.02.002

Escobar, A. (2017). *Designs for the pluriverse: Radical interdependence, autonomy, and the making of worlds*. Duke University Press. https://www.jstor.org/stable/j.ctv11smgs6

Fallman, D. (2008). The interaction design research triangle of design practice, design studies, and design exploration. *Design Issues*, *24*(3). https://www.mitpressjournals.org/doi/abs/10.1162/desi.2008.24.3.4

Fan, M., Shi, S., & Truong, K. N. (2020). Practices and challenges of using think-aloud protocols in industry: An international survey. *Journal of Usability Studies*, *15*(2), 85–102.

Fessenden, T. (2021, April 11). *Design systems 101*. Nielsen Norman Group. https://www.nngroup.com/articles/design-systems-101/

Filippov, S., & Mooi, H. (2010). Innovation project management: A research agenda. *RISUS*, *1*(1).

Fine, G. A., & Deegan, J. G. (1996). Three principles of serendip: Insight, chance, and discovery in qualitative research. *International Journal of Qualitative Studies in Education*, *9*(4), 434–447. https://doi.org/10.1080/0951839960090405

Fink, T. M. A., Reeves, M., Palma, R., & Farr, R. S. (2017). Serendipity and strategy in rapid innovation. *Nature Communications*, *8*(1), Article 1. https://doi.org/10.1038/s41467-017-02042-w

Fiore, S., Wright, P., & Edwards, A. (2005). A pragmatist aesthetics approach to the design of a technological artefact. In *Proceedings of the 4th decennial conference on critical computing: Between sense and sensibility* (pp. 129–132). https://doi.org/10.1145/1094562.1094581

Fischer, B., Peine, A., & Östlund, B. (2020). The importance of user involvement: A systematic review of involving older users in technology design. *The Gerontologist*, *60*(7), e513–e523. https://doi.org/10.1093/geront/gnz163

Følstad, A. (2008). Living labs for innovation and development of information and communication technology: A literature review. *eJOV*, 99–131. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2440026

Frayling, C. (1993). *Research in art and design*. Royal College of Art.

Funke, J. (2014). Solving complex problems: Exploring and control of complex systems. In R. J. Sternberg & P. A. Frensch (Eds.), *Complex problem solving: Principles and mechanisms* (pp. 185–214). Psychology Press.

Gedenryd, H. (1998). *How designers work—Making sense of authentic cognitive activities* [Doctoral dissertation, Cognitive Science, Lund University]. Retrieved from: https://lucris.lub.lu.se/ws/portalfiles/portal/4819156/1484253.pdf

Gernez, E. (2019). *Human-centered, collaborative, field-driven ship design: Implementing field studies for the design of ships in operation* [Doctoral dissertation, Oslo School of Architecture and Design]. https://aho.brage.unit.no/aho-xmlui/handle/11250/2608505

Gernez, E., Nordby, K., Eikenes, J. O., & Hareide, O. S. (2020). A review of augmented reality applications for ship bridges. *Necesse*, *5*(3), 159–186.

Giaccardi, E., & Karana, E. (2015). Foundations of materials experience: An approach for HCI. In *Proceedings of the 33rd annual ACM conference on human factors in computing systems* (pp. 2447–2456). https://doi.org/10.1145/2702123.2702337

Gilhooly, K. J., Georgiou, G. J., Garrison, J., Reston, J. D., & Sirota, M. (2012). Don't wait to incubate: Immediate versus delayed incubation in divergent thinking. *Memory & Cognition*, *40*(6), 966–975. https://doi.org/10.3758/s13421-012-0199-z

Glaser, B. G. (1998). *Doing grounded theory: Issues and discussions*. Sociology Press.

Glaser, B. G., & Strauss, A. L. (1967). *Discovery of grounded theory: Strategies for qualitative research*. Routledge.

Glăveanu, V. P. (2022). What's "inside" the prepared mind? Not things, but relations. In W. Ross & S. Copeland (Eds.), *The art of serendipity* (pp. 23–39). Palgrave Macmillan. https://doi.org/10.1007/978-3-030-84478-3_2

Goodman, E., Stolterman, E., & Wakkary, R. (2011). Understanding interaction design practices. *CHI '11: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems,* pp. 1061–1070. https://doi.org/10.1145/1978942.1979100

Grabowski, M. (2015). Research on wearable, immersive augmented reality (WIAR) adoption in maritime navigation. *Journal of Navigation*, *68*(3), 453–464. https://doi.org/10.1017/S0373463314000873

Gray, C. M. (2016). "It's more of a mindset than a method": UX practitioners' conception of design methods. In *Proceedings of the 2016 CHI conference on human factors in computing systems* (pp. 4044–4055). https://doi.org/10.1145/2858036.2858410

Greene, J. (2022). Ethical design approaches for workplace augmented reality. *Communication Design Quarterly*, *10*(4), 16–26. https://doi.org/10.1145/3531210.3531212

Grossberg, L., Nelson, C., & Treichler, P. A. (1991). Cultural Studies: An Introduction. In L. Grossberg, C. Nelson, & P. Treichler (Eds.), *Cultural Studies* (pp. 1-22). Routledge.

Guo, F., Wu, B., Wah, M., Yang, Z., Blanco-Davis, E., Khalique, A., & Bury, A. (2022). Towards an ergonomic interface in ship bridges: Identification of the design criteria. In U. Asgher (Ed.), *Industrial Cognitive Ergonomics and Engineering Psychology*. AHFE (2022) International Conference, AHFE Open Access, vol 35. AHFE International, USA. http://doi.org/10.54941/ahfe1001609

Hallihan, G. M., & Shu, L. H. (2013). Considering confirmation bias in design and design research. *Journal of Integrated Design and Process Science*, *17*(4), 19–35. https://doi.org/10.3233/jid-2013-0019

Hammond, K. R., & Stewart, T. R. (Eds.). (2001). *The essential Brunswik: Beginnings, explications, applications* (Annotated ed.). Oxford University Press.

Hammond, K. R., Stewart, T. R., Brehmer, B., & Steinmann, D. O. (1975). Social judgment theory. In M. F. Kaplan & S. Schwartz (Eds.), *Human Judgement and Decision Processes* (pp. 271-312). doi: 10.1016/B978-0-12-397250-7.50016-7

Hanington, B., & Martin, B. (2012). *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Rockport Publishers.

Hareide, O. S., Mjelde, F. V., Glomsvoll, O., & Ostnes, R. (2017). Developing a high-speed craft route monitor window. In *Augmented cognition. Enhancing cognition and behavior in complex human environments* (pp. 461–473). https://doi.org/10.1007/978-3-319-58625-0_33

Hareide, O. S., & Ostnes, R. (2017a). Maritime usability study by analysing eye tracking data. *Journal of Navigation*, *70*(5), 927–943. https://doi.org/10.1017/S0373463317000182

Hareide, O. S., & Ostnes, R. (2017b). Scan pattern for the maritime navigator. *TransNav*, *11*(1). https://trid.trb.org/view/1466779

Hareide, O. S., & Porathe, T. (2019, February). Maritime augmented reality. *Coordinates Magazine*, XIX(11), pp. 31–35.

Hari, J. (2022). *Stolen focus: Why you can't pay attention—And how to think deeply again*. Crown.

Harris, M. H. (1966). David Hume. *Library Quarterly*, *36*, 88–98.

Hassenzahl, M., & Tractinsky, N. (2006). User experience - a research agenda. *Behaviour & Information Technology*, 25(2), 91-97. https://doi.org/10.1080/01449290500330331

Hawk, N., Bartle, G., & Romine, M. (2012). The living labs: Innovation in real-life settings. *Quarterly Review of Distance Education*, *13*(4), 225–231.

Holford, W. D. (2020). *Managing knowledge in organizations: A critical pragmatic perspective*. Palgrave Macmillan.

Honeychurch, S. (2023). Pragmatism in practice: Bricolage as a methodological framework for SoTL. *Open Scholarship of Teaching and Learning*, *2*(2), Article 2. https://doi.org/10.56230/osotl.48

Höök, K., & Löwgren, J. (2021). Characterizing interaction design by its ideals: A discipline in transition. *She Ji*, *7*(1), 24–40. https://doi.org/10.1016/j.sheji.2020.12.001

Hussain, Z., Slany, W., & Holzinger, A. (2009). Investigating agile user-centered design in practice: A grounded theory perspective. In A. Holzinger & K. Miesenberger (Eds.), *HCI and usability for e-inclusion* (pp. 279–289). Springer. https://doi.org/10.1007/978-3-642-10308-7_19

Hvidsten, A., & Almqvist, F. (2023). Zooming in and out of complex systems: Exploring frames in incremental participatory design projects. In M. A. Pfannstiel (Ed.), *Human-centered service design for healthcare transformation: Development, innovation, change* (pp. 221–241). Springer International Publishing. https://doi.org/10.1007/978-3-031-20168-4_13

IMO: International Maritime Organization. (2021). *IEC 62288:2021*. Geneva, Switzerland: International Electrotechnical Commission. Retrieved from https://webstore.iec.ch/publication/64659

International Organization for Standardization. (2007). *Ergonomic requirements for office work with visual display terminals (VDTs)—Part 12: Presentation of information* (ISO Standard No. 9241-12:1998). American National Standards Institute.

Johnson-Laird, P. (2004). The history of mental models. In K. I. Manktelow & M. C. Chung (Eds.), *Psychology of reasoning: Theoretical and historical perspectives* (pp. 179–212). Psychology Press. https://doi.org/10.4324/9780203506936
Jones, J. C. (1992). *Design methods* (2nd ed.). John Wiley & Sons.
Jones, P. H. (2014). Systemic design principles for complex social systems. In G. S. Metcalf (Ed.), *Social systems and design* (pp. 91–128). Springer Japan. https://doi.org/10.1007/978-4-431-54478-4_4
Joseph, E., & Zhang, D. (2021). Personality profile of risk-takers: An examination of the Big Five facets. *Journal of Individual Differences*, *42*, 1–10. https://doi.org/10.1027/1614-0001/a000346
Kaplan, K. (2020, August 9). *Application complexity: A 5-layer framework*. Nielsen Norman Group. https://www.nngroup.com/articles/complex-application-design-framework/
Kaptelinin, V., & Nardi, B. (2009). Acting with technology: Activity theory and interaction design. The MIT Press.
Kelly, R. (2018). Design in decline: Breathing new life into an industry through education. *Design Management Journal*, *13*(1), 41–52. https://doi.org/10.1111/dmj.12041
Kingdon, M. (2012). *The science of serendipity: How to unlock the promise of innovation*. Wiley.
Klein, J. (2010). What is artistic research? *Journal for Artistic Research*. https://doi.org/10.22501/jarnet.0004
Knight, J. C. (2002). Safety critical systems: Challenges and directions. In *Proceedings of the 24th International Conference on Software Engineering. ICSE 2002* (pp. 547–550). https://ieeexplore.ieee.org/document/1007998
Kolko, J. (2010). Abductive thinking and sensemaking: The drivers of design synthesis. *Design Issues*, *26*(1), 15–28. https://doi.org/10.1162/desi.2010.26.1.15
Koskinen, I. (2014). Four Cultures of Analysis in Design Research. In P. A. Rodgers & J. Yee (Eds.), *The Routledge Companion to Design Research* (1st ed., pp. 217–225). Routledge. https://doi.org/10.4324/9781315758466
Krippendorff, K. (2005). *The semantic turn: A new foundation for design*. CRC Press.
Krosnick, J. A. (2018). Questionnaire design. In D. L. Vannette & J. A. Krosnick (Eds.), *The Palgrave handbook of survey research* (pp. 439–455). Springer International Publishing. https://doi.org/10.1007/978-3-319-54395-6_53
Kuhn, T. S. (1979). *the essential tension: Selected studies in scientific tradition and change*. University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/E/bo5970650.html
Kumar, V. (2012). *101 design methods: A structured approach for driving innovation in your organization*. Wiley.
Kunrath, K., Cash, P., & Kleinsmann, M. (2020). Designers' professional identity: Personal attributes and design skills. *Journal of Engineering Design*, *31*(6), 297–330. https://doi.org/10.1080/09544828.2020.1743244
Kurtz, C. F., & Snowden, D. J. (2003). The new dynamics of strategy: Sense-making in a complex and complicated world. *IBM Systems Journal*, *42*(3), 462–483. https://doi.org/10.1147/sj.423.0462
Laera, F., Fiorentino, M., Evangelista, A., Boccaccio, A., Manghisi, V. M., Gabbard, J., Gattullo, M., Uva, A. E., & Foglia, M. M. (2021). Augmented reality for maritime navigation data visualisation: A systematic review, issues and perspectives. *Journal of Navigation*, *74*(5), 1073–1090. https://doi.org/10.1017/S0373463321000412

Lane, J. N., Ganguli, I., Gaule, P., Guinan, E., & Lakhani, K. R. (2021). Engineering serendipity: When does knowledge sharing lead to knowledge production? *Strategic Management Journal*, *42*(6), 1215–1244. https://doi.org/10.1002/smj.3256

Lavery, B. (2006). Introduction. *A Seaman's Pocket-Book* (pp. 2-3). Conway.

Leblanc, T. (2015, September 3–4). Leblanc, T. (2015). Sketching as a thinking process. *In Proceedings of the International Conference on Engineering and Product Design Education.* Loughborough University, Design School, Loughborough, UK. Retrieved from https://api.semanticscholar.org/CorpusID:65370404

Lewis, D. K. (1980). A subjectivist's guide to objective chance. In R. C. Jeffrey (Ed.), *Studies in Inductive Logic and Probability, Volume II* (pp. 263-293). University of California Press.

Liang, R.-H. (2012). Designing for unexpected encounters with digital products: Case studies of serendipity as felt experience. *International Journal of Design*, *6*(1). http://www.ijdesign.org/index.php/IJDesign/article/view/1059/402

Liestman, D. (1992). Chance in the midst of design: Approaches to library research serendipity. *RQ*, *31*(4), 524–532.

Ligita, T., Nurjannah, I., Wicking, K., Harvey, N., & Francis, K. (2022). From textual to visual: The use of concept mapping as an analytical tool in a grounded theory study. *Qualitative Research*, *22*(1), 126–142. https://doi.org/10.1177/1468794120965362

Lim, Y., Stolterman, E., Jung, H., & Donaldson, J. (2007). Interaction gestalt and the design of aesthetic interactions. In *Proceedings of the 2007 conference on designing pleasurable products and interfaces* (pp. 239–254). https://doi.org/10.1145/1314161.1314183

Lindlbauer, D., Feit, A., & Hilliges, O. (2019). Context-Aware Online Adaptation of Mixed Reality Interfaces. *UIST '19: Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pp. 147–160. https://doi.org/10.1145/3332165.3347945

Lock, G., & Sikk, J. (2022). Accident and serendipity in music composition, improvisation and performance art. In W. Ross & S. Copeland (Eds.), *The art of serendipity* (pp. 191–219). Springer Nature.

Löwgren, J., & Stolterman, E. (2007). *Thoughtful interaction design: A design perspective on information technology* (New ed.). MIT Press.

Löwgren, J. (2014, January 1). Interaction Design - brief intro. Interaction Design Foundation - IxDF. Retrieved from https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/interaction-design-brief-intro

Luck, R. (2014). Towards the formulation of a research question: Guidance through the glass bead game of research design. In P. A. Rodgers & J. Yee (Eds.), *The Routledge Companion to Design Research* (pp. 142–150). Routledge.

Lurås, S. (2016a). *Systemic design in complex contexts: An enquiry through designing a ship's bridge* [Doctoral dissertation, Oslo School of Architecture and Design]. https://brage.bibsys.no/xmlui/handle/11250/2380135

Lurås, S. (2016b). Systems intertwined: A systemic view on the design situation. *Design Issues*, *32*(3), 30–41.

Lurås, S., Lützhöft, M., & Sevaldson, B. (2015). Meeting the complex and unfamiliar: Lessons from design in the offshore industry. *International Journal of Design*, 9(2), pp. 141-154.

Lurås, S., & Nordby, K. (2015). Shaping Designers' Sea Sense: A Guide for Design-Driven Field Research at Sea. *International Conference on Marine Design 2015*, 2-3 September 2015, London, UK. DOI: 10.3940/rina.md.2015.11.

Lutz, C., Pieter Hoffmann, C., & Meckel, M. (2017). Online serendipity: A contextual differentiation of antecedents and outcomes. *Journal of the Association for Information Science and Technology*, *68*(7), 1698–1710. https://doi.org/10.1002/asi.23771

Lützhöft, M. H., Grech, M. R., & Porathe, T. (2011). Information Environment, Fatigue, and Culture in the Maritime Domain. *Reviews of Human Factors and Ergonomics*, *7*(1), 280–322. https://doi.org/10.1177/1557234x11410391

Lvov, M. S., & Popova, H. V. (2019). Simulation technologies of virtual reality usage in the training of future ship navigators. *Educational Dimension*, 1(1), 159–180. https://doi.org/10.31812/educdim.v53i1.3840

Mäkelä, A. M., & Nimkulrat, N. (2011). Reflection and documentation in practice-led design research. *Nordes*, *4*, Article 4. https://archive.nordes.org/index.php/n13/article/view/98

Makri, S., & Blandford, A. (2012). Coming across information serendipitously – Part 1: A process model. *Journal of Documentation*, *68*(5), Article 5.

Makri, S., Blandford, A., Woods, M., Sharples, S., & Maxwell, D. (2014). "Making my own luck": Serendipity strategies and how to support them in digital information environments. *Journal of the Association for Information Science and Technology*, *65*(11), 2179–2194. https://doi.org/10.1002/asi.23200

Mall, D. (2023). *Do design systems limit creativity? Dan Mall says no*. Dribble Education. https://dribbble.com/resources/creativity-and-design-systems

Mallam, S. C., Nazir, S., & Renganayagalu, S. K. (2019). Rethinking maritime education, training, and operations in the digital era: Applications for emerging immersive technologies. *Journal of Marine Science and Engineering*, *7*(12), Article 12. https://doi.org/10.3390/jmse7120428

March, L. (1976). The logic of design. In L. March (Ed.), *The Architecture of Form* (pp. 16–40). Cambridge University Press.

Markopoulos, E., & Luimula, M. (2020). Immersive safe oceans technology: Developing virtual onboard training episodes for maritime safety. *Future Internet*, *12*(5), Article 5. https://doi.org/10.3390/fi12050080

Marques, B., Silva, S., Teixeira, A., Dias, P., & Santos, B. S. (2022). A vision for contextualized evaluation of remote collaboration supported by AR. *Computers & Graphics*, *102*, 413–425. https://doi.org/10.1016/j.cag.2021.10.009

Matthews, B., Shannon, B., & Roxburgh, M. (2023). Destroy all humans: The dematerialisation of the designer in an age of automation and its impact on graphic design—A literature review. *International Journal of Art & Design Education*, *42*(3), 367–383. https://doi.org/10.1111/jade.12460

Maxwell, D., Woods, M., Makri, S., Bental, D., Kefalidou, G., & Sharples, S. (2012). Designing a Semantic Sketchbook to Create Opportunities for Serendipity. *In Proceedings of the 26th BCS Conference on Human Computer Interaction (HCI)* (pp. 357-362).

McBirnie, A. (2008). Seeking serendipity: The paradox of control. *Aslib Proceedings*, *60*(6), 600–618. https://doi.org/10.1108/00012530810924294

McCay-Peet, L., & Toms, E. G. (2010). The process of serendipity in knowledge work. In *Proceedings of the third symposium on information interaction in context* (pp. 377–382). https://doi.org/10.1145/1840784.1840842

McCay-Peet, L., & Toms, E. G. (2015). Investigating serendipity: How it unfolds and what may influence it. *Journal of the Association for Information Science and Technology*, *66*(7), 1463–1476. https://doi.org/10.1002/asi.23273

McCay-Peet, L., & Toms, E. G. (2018). *Researching serendipity in digital information environments*. https://doi.org/10.1007/978-3-031-02312-5

McCay-Peet, L., & Wells, P. G. (2017). Serendipity in the sciences – Exploring the boundaries. *Proceedings of the Nova Scotian Institute of Science*, *49*(1), Article 1. https://doi.org/10.15273/pnsis.v49i1.6981

McCoy, B. M. (2009). *Advanced statistical mechanics*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199556632.003.0016

McCulloch, A. (2022). Serendipity in doctoral education: The importance of chance and the prepared mind in the PhD. *Journal of Further and Higher Education*, *46*(2), 258–271. https://doi.org/10.1080/0309877X.2021.1905157

Merriam-Webster. (n.d.-a). *Serendipity*. In *Merriam-Webster.com dictionary*. https://www.merriam-webster.com/dictionary/serendipity

Merriam-Webster. (n.d.-b). *Timing*. In *Merriam-Webster.com dictionary*. https://www.merriam-webster.com/dictionary/timing

Merton, R. K. (1948). The bearing of empirical research upon the development of social theory. *American Sociological Review*, *13*(5), 505–515.

Merton, R. K., & Barber, E. G. (2004). *the travels and adventures of serendipity: A study in sociological semantics and the sociology of science*. Princeton University Press.

Meyer, M. W., & Norman, D. (2020). Changing design education for the 21st century. *She Ji*, *6*(1), 13–49. https://doi.org/10.1016/j.sheji.2019.12.002

Microsoft. (2022, June 8). *Start designing and prototyping—Mixed reality*. Microsoft Mixed Reality. https://learn.microsoft.com/en-us/windows/mixed-reality/design/design

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, *E77-D*(12), 1321–1329.

Milovanovic, J., Moreau, G., Siret, D., & Miguet, F. (2017, July). Virtual and Augmented Reality in Architectural Design and Education: An Immersive Multimodal Platform to Support Architectural Pedagogy. In Çağdaş, G., Özkar, M., Gül, L. F., & Gürer, E. (Eds.), *Proceedings of the 17th International Conference, CAAD Futures 2017*. Istanbul, Turkey. Retrieved from https://hal.science/hal-01586746

Mitchell, M. (2011). *Complexity: A guided tour* (Illustrated ed.). Oxford University Press.

Moggridge, B. (2007). *Designing interactions*. MIT Press.

Morgeson, F. P., & DeRue, D. S. (2006). Event criticality, urgency, and duration: Understanding how events disrupt teams and influence team leader intervention. *The Leadership Quarterly*, *17*(3), 271–287. https://doi.org/10.1016/j.leaqua.2006.02.006

Morrison, A. (2017). Ten green bottles: Reflecting on the exegesis in the thesis by compilation model. In L. Vaughan (Ed.), *Practice-based design research* (pp. 120–127). Bloomsbury Academic.

Morville, P., & Rosenfeld, L. (2007). *Information architecture for the world wide web: Designing large-scale web sites* (3rd ed.). O'Reilly Media.

Moshman, D., & Geil, M. (1998). Collaborative reasoning: Evidence for collective rationality. *Thinking & Reasoning*, *4*(3), 231–248. https://doi.org/10.1080/135467898394148

Napier, N., & Vuong, Q. H. (2013). Serendipity as a strategic advantage? *Strategic management in the 21st century*, 1, pp. 175–199. https://scholarworks.boisestate.edu/internationalbusiness_facpub/16

Nelson, H. G. (2022). Systemic design as born from the Berkeley Bubble matrix. *Contexts*, *1*, Article v1001.

Nelson, H. G., & Stolterman, E. (2003). Design judgement: Decision-making in the "real" world. *The Design Journal*, *6*(1), 23–31. https://doi.org/10.2752/146069203790219344

Nelson, H. G., & Stolterman, E. (2014). *The design way: Intentional change in an unpredictable world* (2nd ed.). MIT Press.

Niederman, F., & March, S. (2019). The "theoretical lens" concept: We all know what it means, but do we all know the same thing? *Communications of the Association for Information Systems*, *44*(1). https://doi.org/10.17705/1CAIS.04401

Nordby, K. (2010). Conceptual designing and technology: Short-range RFID as design material. *International Journal of Design*, *4*(1), 29–44.

Nordby, K. (2011). *Between the tag and the screen: Redesigning short-range RFID as design material* (Doctoral thesis, The Oslo School of Architecture and Design). http://hdl.handle.net/11250/93044

Norman, D. A. (1988). *The design of everyday things* (Revised ed.). Basic Books.

Norman, D. A. (2023). *Design for a better world: Meaningful, sustainable, humanity centered*. MIT Press.

Olshannikova, E., Olsson, T., Huhtamäki, J., Paasovaara, S., & Kärkkäinen, H. (2020). From chance to serendipity: Knowledge workers' experiences of serendipitous social encounters. *Advances in Human-Computer Interaction*, *2020*, Article e1827107. https://doi.org/10.1155/2020/1827107

Ozkan, N. (2019). Imperfections underlying the manifesto for agile software development. In *2019 1st International Informatics and Software Engineering Conference (UBMYK)* (pp. 1–6). https://doi.org/10.1109/UBMYK48245.2019.8965504

Park, J., & Kim, Y. (2018). A novel speech-act coding scheme to visualize the intention of crew communications to cope with simulated off-normal conditions of nuclear power plants. *Reliability Engineering & System Safety*, *178*, 236–246. https://doi.org/10.1016/j.ress.2018.05.013

Patten, M. L., & Galvan, M. C. (2019). *Proposing empirical research: A guide to the fundamentals*. Routledge.

Peirce, C. S. (1958). *Collected papers of Charles Sanders Peirce, Volumes VII and VIII: Science and philosophy and reviews, correspondence and bibliography* (A. W. Burks, Ed.). Belknap Press.

Petroliumstilsynet. (2023). *Main Report 2022: Trends in the Norwegian Continental Shelf. Risk Level in Norwegian Petroleum Activities*. [English translation].

Petroski, H. (2013). *Success through failure: The paradox of design*. Princeton University Press. https://doi.org/10.1515/9781400849116

Piñeyro, A. (2022). Fostering creative opportunities by embracing the accidental within practices of making. In W. Ross & S. Copeland (Eds.), *The art of serendipity* (pp. 127–156). Palgrave Macmillan.

Plonka, L., Sharp, H., Gregory, P., & Taylor, K. (2014). UX design in agile: A DSDM case study. In G. Cantone & M. Marchesi (Eds.), *Agile processes in software engineering and extreme programming* (pp. 1–15). Springer International Publishing. https://doi.org/10.1007/978-3-319-06862-6_1

Poth, A., Kottke, M., & Riel, A. (2020). Scaling agile – A large enterprise view on delivering and ensuring sustainable transitions. In A. Przybyłek & M. E. Morales-Trujillo (Eds.), *Advances in agile and user-centred software engineering* (pp. 1–18). Springer International Publishing. https://doi.org/10.1007/978-3-030-37534-8_1

Pratt, M. G., Sonenshein, S., & Feldman, M. S. (2022). Moving beyond templates: A bricolage approach to conducting trustworthy qualitative research. *Organizational Research Methods*, *25*(2), 211–238. https://doi.org/10.1177/1094428120927466

Preece, J., Sharp, H., & Rogers, Y. (2015). *Interaction design: Beyond human-computer interaction*. John Wiley & Sons.

Procee, S., Borst, C., van Paassen, R., & Mulder, M. (2017). Toward functional augmented reality in marine navigation: A cognitive work analysis. *16th Conference on Computer and IT Applications in the Maritime Industries*. http://resolver.tudelft.nl/uuid:67f92410-9e5a-452f-8fba-713f8d084cd2

Procee, S., Borst, C., van Paassen, R., & Mulder, M. (2018). Using augmented reality to improve collision avoidance and resolution. *Proceedings of the 17th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT '18)*. https://repository.tudelft.nl/islandora/object/uuid%3A42f31d3a-d18b-41b9-9b09-bf1c0643a96c

Procee, S., Borst, C., van Passen, R., & Mulder, M. (2020, August). Measuring the effect of augmented reality on situational awareness. *19th International Conference on Computer and IT Applications in the Maritime Industries.* COMPIT'20, Potignano, Italy.

Rajlich, V. (2014). Software evolution and maintenance. In *Future of Software Engineering Proceedings* (pp. 133–144). https://doi.org/10.1145/2593882.2593893

Rauch, M., & Ansari, S. (2022). From "publish or perish" to societal impact: Organizational repurposing towards responsible innovation through creating a medical platform. *Journal of Management Studies*, *59*(1), 61–91. https://doi.org/10.1111/joms.12737

Reeves, S. (2019). How UX practitioners produce findings in usability testing. *ACM Transactions on Computer-Human Interaction*, *26*(1), 1–38. https://doi.org/10.1145/3299096

Resmini, A., & Rosati, L. (2011). A brief history of information architecture. *Journal of Information Architecture*, *3*, 33–46. https://doi.org/10.55135/1015060901/112.006/3.024

Reviglio, U. (2017). Serendipity by design? How to turn from diversity exposure to diversity experience to face filter bubbles in social media. In I. Kompatsiaris, J. Cave, A. Satsiou, G. Carle, A. Passani, E. Kontopoulos, S. Diplaris, & D. McMillan (Eds.), *Internet science* (pp. 281–300). Springer International Publishing. https://doi.org/10.1007/978-3-319-70284-1_22

Reviglio, U. (2019). Serendipity as an emerging design principle of the infosphere: Challenges and opportunities. *Ethics and Information Technology*, *21*(2), 151–166. https://doi.org/10.1007/s10676-018-9496-y

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Science*, *4*(2), 155–169.

Ritter, S. M., & Dijksterhuis, A. (2014). Creativity—The unconscious foundations of the incubation period. *Frontiers in Human Neuroscience*, *8*, Article 215. https://doi.org/10.3389/fnhum.2014.00215
Rivoal, I., & Salazar, N. B. (2013). Contemporary ethnographic practice and the value of serendipity. *Social Anthropology*, *21*(2), 178–185. https://doi.org/10.1111/1469-8676.12026
Roberts, R. M. (1989). *Serendipity: Accidental discoveries in science*. Wiley.
Robles, E., & Wiberg, M. (2010). Texturing the “material turn” in interaction design. In *Proceedings of the fourth international conference on tangible, embedded, and embodied interaction* (pp. 137–144). https://doi.org/10.1145/1709886.1709911
Rocque, D. S. R. (2022). *Integrating cutting-edge technologies into learning and development to enhance innovation*. SSRN. https://doi.org/10.2139/ssrn.4215019
Roesler, A., & Woods, D. (2007). Designing for Expertise. In H.N.J. Schifferstein & P. Hekkert (Eds.), *Product Experience: A Multidisciplinary Approach* (pp. 215-237). Elsevier.
Rogers, M. (2012). Contextualizing theories and practices of bricolage research. *The Qualitative Report*, *17*(48), 1–17. https://doi.org/10.46743/2160-3715/2012.1704
Rogers, Y. (2004). New theoretical approaches for human-computer interaction. *Annual Review of Information Science and Technology*, *38*, 87–143.
Ross, W. (2022). Heteroscalar serendipity and the importance of accidents. In W. Ross & S. Copeland (Eds.), *The art of serendipity* (pp. 75–99). Springer International Publishing. https://doi.org/10.1007/978-3-030-84478-3_4
Ross, W. (2023). Serendipitous cognition—The systematic consideration of the accidental genesis of new ideas. In S. Copeland, W. Ross, & M. Sand (Eds.), *Serendipity science: An emerging field and its methods* (pp. 167–186). Springer International Publishing. http://ebookcentral.proquest.com/lib/ahono/detail.action?docID=30647822
Ross, W., & Vallée-Tourangeau, F. (2021). Microserendipity in the creative process. *Journal of Creative Behavior*, *55*(3), 661–672. https://doi.org/10.1002/jocb.478
Rowen, A., Grabowski, M., & Rancy, J.-P. (2021). Moving and improving in safety-critical systems: Impacts of head-mounted displays on operator mobility, performance, and situation awareness. *International Journal of Human-Computer Studies*, *150*, Article 102606. https://doi.org/10.1016/j.ijhcs.2021.102606
Rowen, A., Grabowski, M., Rancy, J.-P., & Crane, A. (2019). Impacts of wearable augmented reality displays on operator performance, situation awareness, and communication in safety-critical systems. *Applied Ergonomics*, *80*, 17–27. https://doi.org/10.1016/j.apergo.2019.04.013
Royce, W. W. (1987). Managing the development of large software systems: Concepts and techniques. In *Proceedings of the 9th International Conference on Software Engineering* (pp. 328–338).
Rubin, J., Chisnell, D., & Spool, J. (2008). *Handbook of usability testing: How to plan, design, and conduct effective tests* (2nd ed.). Wiley.
Rubin, V., Burkell, J., & Quan-Haase, A. (2011). Facets of serendipity in everyday chance encounter: A grounded theory approach to blog analysis. *Information Research*, *16*(3). https://ir.lib.uwo.ca/fimspub/56

Rust, C. (2004). Design enquiry: Tacit knowledge and invention in science. *Design Issues*, *20*(4), 76–85.

Rylander Eklund, A., Navarro Aguiar, U., & Amacker, A. (2021). Design thinking as sensemaking – Developing a pragmatist theory of practice to (re)introduce sensibility. *Journal of Product Innovation Management*. https://doi.org/10.1111/jpim.12604

Saffer, D. (2010). *Designing for interaction: Creating innovative applications and devices*. New Riders.

Sag, A. (2018, March 9). Context is everything when it comes to AR. *Moor Insights & Strategy*. https://staging3.moorinsightsstrategy.com/context-is-everything-when-it-comes-to-ar/

Salzman, P. C. (2002). On Reflexivity on JSTOR. *American Anthropologist*, *104*(3), pp. 805–813.

Sanders, E. B.-N. (2000). Generative tools for co-designing. In S. A. R. Scrivener, L. J. Ball, & A. Woodcock (Eds.), *Collaborative design* (pp. 3–12). Springer. https://doi.org/10.1007/978-1-4471-0779-8_1

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign*, *4*(1), 5–18. https://doi.org/10.1080/15710880701875068

Santos, J., & Williamson, P. (2022). *Discovering strategy: Dealing with uncertainty by harnessing serendipity*. SSRN. https://doi.org/10.2139/ssrn.4274207

Sarkar, P., & Chakrabarti, A. (2011). Assessing design creativity. *Design Studies*, *32*(4), 348–383. https://doi.org/10.1016/j.destud.2011.01.002

Schaathun, H. G. (2022). Where Schön and Simon agree: The rationality of design. *Design Studies*, *79*, Article 101090. https://doi.org/10.1016/j.destud.2022.101090

Schlick, C. M., Winkelholz, C., Motz, F., Duckwitz, S., & Grandt, M. (2010). Complexity assessment of human–computer interaction. *Theoretical Issues in Ergonomics Science*, *11*(3), 151–173. https://doi.org/10.1080/14639220802609903

Scholz, R., & Tietje, O. (2002). *Embedded case study methods: Integrating quantitative and qualitative knowledge*. SAGE Publications.

Schön, D. A. (1984). *The reflective practitioner: How professionals think in action*. Basic Books.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. *Research in Engineering Design*, *3*(3), 131–147. https://doi.org/10.1007/BF01580516

Schønheyder, J. F. (2019). *Method development for the design of safety-critical systems: The space between design research and professional design practice* [Doctoral dissertation, Oslo School of Architecture and Design].

Schønheyder, J. F., & Nordby, K. (2018). The use and evolution of design methods in professional design practice. *Design Studies*, *58*, 36–62. https://doi.org/10.1016/j.destud.2018.04.001

Schopenhauer, A. (2016). *Arthur Schopenhauer: The world as will and presentation*. Routledge. https://doi.org/10.4324/9781315507897

Schwandt, D. (2005). When managers become philosophers: Integrating learning with sensemaking. *Academy of Management Learning & Education*, 4(2), 176–192. https://doi.org/10.5465/AMLE.2005.17268565

Seifert, C. M., Meyer, D. E., Davidson, N., Patalano, A. L., & Yaniv, I. (1995). Demystification of cognitive insight: Opportunistic assimilation and the prepared-mind perspective. In R. J. Sternberg & J. E. Davidson (Eds.), *The Nature of Insight* (pp. 65–124). The MIT Press.

Sengers, P., & Gaver, B. (2006). Staying open to interpretation: Engaging multiple meanings in design and evaluation. In *Proceedings of the 6th conference on designing interactive systems* (pp. 99–108). https://doi.org/10.1145/1142405.1142422

Sevaldson, B. (2010). Discussions and movements in design research: A systems approach to practice research in design. *FORMakademisk* 3 (1), pp. 8–35. https://brage.bibsys.no/xmlui/handle/11250/92982

Sevaldson, B. (2022). *Designing complexity: The methodology and practice of systems oriented design*. Common Ground Research Networks.

Sharma, A., Nazir, S., & Ernstsen, J. (2019). Situation awareness information requirements for maritime navigation: A goal directed task analysis. *Safety Science*, *120*, 745–752. https://doi.org/10.1016/j.ssci.2019.08.016

Sikt. (2023). *Create a data management plan*. https://sikt.no/en/data-management-plan

Simon, H. A. (1973). The structure of ill structured problems. *Artificial Intelligence*, *4*(3), 181–201. https://doi.org/10.1016/0004-3702(73)90011-8

Simon, H. A. (1990). Bounded rationality. In J. Eatwell, M. Milgate, & P. Newman (Eds.), *Utility and probability* (pp. 15–18). Palgrave Macmillan UK. https://doi.org/10.1007/978-1-349-20568-4_5

Smets, A. (2022). Designing for serendipity: A means or an end? *Journal of Documentation*, *79*(3), 589–607. https://doi.org/10.1108/JD-12-2021-0234

Smith, W., & Lewis, M. (2022). *Both/and thinking: Embracing creative tensions to solve your toughest problems*. Harvard Business Review Press.

Snowden, D. J., & Boone, M. E. (2007). A leader's framework for decision making. A leader's framework for decision making. *Harvard Business Review*, *85*(11), 68–76, 149.

Snyder, C. (2003). *Paper prototyping: The fast and easy way to design and refine user interfaces*. Morgan Kaufmann.

Sohi, A. J., Hertogh, M., Bosch-Rekveldt, M., & Blom, R. (2016). Does lean & Agile project management help coping with project complexity? *Procedia – Social and Behavioral Sciences*, *226*, 252–259. https://doi.org/10.1016/j.sbspro.2016.06.186

Stacey, R. D. (1996). *Strategic management and organisational dynamics: The challenge of complexity to ways of thinking about organisations*. Pearson.

Stappers, P. J., & Giaccardi, E. (2017). Research through Design. In M. Soegaard & R. Friis-Dam (Eds.), *The encyclopedia of human-computer interaction* (pp. 1–94). Interaction Design Foundation. https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design

Stephanidis, C., Salvendy, G., Antona, M., Chen, J. Y. C., Dong, J., Duffy, V. G., Fang, X., Fidopiastis, C., Fragomeni, G., Fu, L. P., Guo, Y., Harris, D., Ioannou, A., Jeong, K., Konomi, S., Krömker, H., Kurosu, M., Lewis, J. R., Marcus, A., … Zhou, J. (2019). Seven HCI grand challenges. *International Journal of Human–Computer Interaction*, *35*(14), 1229–1269. https://doi.org/10.1080/10447318.2019.1619259

Sternberg, R. J. (2011). *Cognitive psychology* (6th ed.). Cengage Learning.

Stokel-Walker, C., & Van Noorden, R. (2023). What ChatGPT and generative AI mean for science. *Nature*, *614*(7947), 214–216. https://doi.org/10.1038/d41586-023-00340-6

Stolterman, E. (2008). The nature of design practice and implications for interaction design research. *International Journal of Design*, *2*(1). https://www.proquest.com/docview/921472711/abstract/FEA560BEB01D4C?parentSessionId=0n1vCgJyy2oenLjG%2FxEEHPKoiFhgiOun8bSGOGdZI8M%3D

Stolterman, E., & Wiberg, M. (2010). Concept-driven interaction design research. *Human–Computer Interaction*, *25*(2), 95–118. https://doi.org/10.1080/07370020903586696

Stone, D., Jarrett, C., Woodroffe, M., & Minocha, S. (2005). *User interface design and evaluation*. Elsevier.

Strange, E., & Nordby, K. (2022). Self-Scaling Open Innovation Pathways: Accelerating integration of augmented reality into the maritime sector. In *Proceedings of Relating Systems Thinking and Design* (Vol. RSD11, Article No. 161). University of Brighton. Retrieved from https://rsdsymposium.org/self-scaling-open-innovation-pathways

Suchman, L. A. (1985). *Plans and situated actions: The problem of human-machine communication*. Cambridge University Press.

Sun, X., Sharples, S., & Makri, S. (2011). A user-centred mobile diary study approach to understanding serendipity in information research. *Information Research*, 16(3).

Tashakkori, A., & Creswell, J. (2007). Editorial: The new era of mixed methods. *Journal of Mixed Methods Research*, *1*, 3–7. https://doi.org/10.1177/2345678906293042

Thompson, D. C., & Copeland, S. M. (2023). Serendipity in research and development: The promise of putting into place patterns for paying attention. *Drug Discovery Today*, 28(8), 103648. Doi: 10.1016/j.drudis.2023.103648. PMID: 37263388.

Topolinski, S., & Reber, R. (2010). Gaining insight into the “aha” experience. *Current Directions in Psychological Science*, *19*(6), 402–405. https://doi.org/10.1177/0963721410388803

Trischler, J., Pervan, S., Kelly, S., & Scott, D. (2018). The value of codesign: The effect of customer involvement in service design teams. *Journal of Service Research*, *21*, 75–100. https://doi.org/10.1177/1094670517714060

Turner, R., & Kasperczyk, H. (2022). Space for the unexpected: Serendipity in immersive theatre. In W. Ross & S. Copeland (Eds.), *The art of serendipity* (pp. 101–125). Palgrave Macmillan. https://doi.org/10.1007/978-3-030-84478-3

Turner, S. P. (2012). Double Heuristics and Collective Knowledge: The Case of Expertise. *Studies in Emergent Order*, 5, 64-85.

Valkenburg, R., & Dorst, K. (1998). The reflective practice of design teams. *Design Studies*, *19*(3), 249–271. https://doi.org/10.1016/S0142-694X(98)00011-8

Vallery-Radot, R. (1911). *The life of Pasteur* (R. L. Devonshire, Trans.; W. Osler, Foreword). Constable. https://www.biodiversitylibrary.org/bibliography/25680

Van Andel, P. (1994). Anatomy of the unsought finding. Serendipity: Origin, history, domains, traditions, appearances, patterns and programmability. *British Journal for the Philosophy of Science*, *45*(2), 631–648.

van den Oever, F., Fjeld, M., & Sætrevik, B. (2023). A systematic literature review of augmented reality for maritime collaboration. *International Journal of Human-Computer Interaction*. Advance online publication. https://doi.org/10.1080/10447318.2023.2209838

Vantomme, G., & Crassous, J. (2021). Pasteur and chirality: A story of how serendipity favors the prepared minds. *Chirality*, *33*(10), 597–601. https://doi.org/10.1002/chir.23349

Verganti, R., Vendraminelli, L., & Iansiti, M. (2020). Innovation and design in the age of artificial intelligence. *Journal of Product Innovation Management*, 37(3), pp. 212–227). https://doi.org/10.1111/jpim.12523

Vidgen, R., & Wang, X. (2009). Coevolving systems and the organization of Agile software development. *Information Systems Research*, *20*(3), 355–376. https://doi.org/10.1287/isre.1090.0237

Vink, J. (2023). Embodied, Everyday systemic design—A pragmatist perspective. *Design Issues*, *39*(4), 35–48. https://doi.org/10.1162/desi_a_00731

von der Au, S., Rauschnabel, P. A., Felix, R., & Hinsch, C. (2023). Context in augmented reality marketing: Does the place of use matter? *Psychology & Marketing*, 40(11), pp. 2447-2463. https://doi.org/10.1002/mar.21814

von Hippel, E., & von Krogh, G. (2016). CROSSROADS—Identifying viable "need–solution pairs": Problem solving without problem formulation. *Organization Science*, *27*(1), 207–221. https://doi.org/10.1287/orsc.2015.1023

Vuong, Q.-H. (2022). *A new theory of serendipity: Nature, emergence and mechanism*. Walter De Gruyter.

Ward, C., Stolterman, E., & Beck, J. (2018). How emerging technologies influence designing – The case of conversational agents and interaction design. In *Design Research Society Conference DRS Biennial Conference* Series (pp. 25–28). URL: https://dl.designresearchsociety.org/drs-conference-papers/drs2018/researchpapers/91.

Watson, L. (2015). What is Inquisitiveness. *American Philosophical Quarterly* 52 (3), pp. 273–287.

Web Accessibility Initiative. (2018). *WCAG 2 overview*. https://www.w3.org/WAI/standards-guidelines/wcag/

Weick, K. E. (1989). Theory construction as disciplined imagination. *Academy of Management Review*, *14*(4), 516–531. https://doi.org/10.2307/258556

Weick, K. E. (1995). *Sensemaking in organizations*. SAGE.

Weick, K. E. (1998). Introductory essay—Improvisation as a mindset for organizational analysis. *Organization Science*, *9*(5), 543–555. https://doi.org/10.1287/orsc.9.5.543

Weick, K. E. (2004). Designing for thrownness. In R. Boland jr. & F. Collopy (Eds.), *Managing as designing* (pp. 74–78). Stanford University Press. https://doi.org/10.1515/9780804767439-008

Weick, K. E., Sutcliffe, K., & Obstfeld, D. (2005). Organizing and the process of sensemaking. *Organization Science*, *16*, 409–421. https://doi.org/10.1287/orsc.1050.0133

Wiberg, M. (2018). *The materiality of interaction*. MIT Press. https://mitpress.mit.edu/9780262037518/the-materiality-of-interaction/

Wickens, C. D. (2008). Situation awareness: Review of Mica Endsley's 1995 articles on situation awareness theory and measurement. *Human Factors*, *50*(3), 397–403. https://doi.org/10.1518/001872008X288420

Wingo, R. S., & Tanik, M. M. (2015). Using an Agile software development methodology for a complex problem domain. In *SoutheastCon 2015* (pp. 1–8). https://doi.org/10.1109/SECON.2015.7132890

Winograd, T. (2006). Designing a new foundation for design. *Communications of the ACM*, *49*(5), 71–74. https://doi.org/10.1145/1125944.1125978

Wolf, B. (2005). Brunswik's original lens model. *Philosophy.* https://www.albany.edu/cpr/brunswik/notes/WolfOriginalLens2005.pdf
Woodman, R. (2002). *The history of the ship: The comprehensive story of seafaring from the earliest times to the present day*. Lyons Press.
Yee, J., & Bremner, C. (2011, May). *Methodological bricolage: What does it tell us about design?* In: *Doctoral Design Education Conference*, 23-25 May 2011, Hong Kong Polytechnic, Hong Kong. https://nrl.northumbria.ac.uk/id/eprint/8822/
Yilmaz, S., & Seifert, C. M. (2011). Creativity through design heuristics: A case study of expert product design. *Design Studies*, *32*(4), 384–415. https://doi.org/10.1016/j.destud.2011.01.003
Yin, R. K. (2013). *Case study research: Design and methods*. SAGE Publications.
Zeller, M., Miller, E., & Paniagua, S. (2019, September 16). *HoloLens (1st gen) hardware* [Documentation]. Microsoft. https://docs.microsoft.com/en-us/hololens/hololens1-hardware
Zierock, B., Jungblut, A., & Senn, N. (2023). Chaotic customer centricity. In C. Stephanidis, M. Antona, S. Ntoa, & G. Salvendy (Eds.), *HCI International 2023 posters* (pp. 189–198). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-35989-7_24
Zimmerman, J., Stolterman, E., & Forlizzi, J. (2010). An analysis and critique of research through design: Towards a formalization of a research approach. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems* (pp. 310–319). ACM. Doi:10.1145/1858171.1858228.
Zimmerman, B. (2001). *Ralph Stacey's Agreement & Certainty Matrix*. Schulich School of Business, York University, Toronto, Canada. https://www.nccmt.ca/uploads/media/media/0001/03/219b71c0f7ff72221e90bd4b6b7c537466c18301.pdf
Zorzetti, M., Signoretti, I., Salerno, L., Marczak, S., & Bastos, R. (2022). Improving Agile software development using user-centered design and lean startup. *Information and Software Technology*, *141*, Article 106718. https://doi.org/10.1016/j.infsof.2021.106718

# PART II (Publication 1–6)

# PUBLICATION 1

Frydenberg, S., Nordby, K., & Eikenes, J. O. H. (2018). Exploring designs of augmented reality systems for ship bridges in Arctic waters. In *Proceedings of the RINA international conference on human factors*. Royal Institution of Naval Architects.

Paper originally presented at RINA - International Conference on Human Factors, 26 –27 September 2018, London.
Reproduced with the kind permission of the Royal Institution of Naval Architects.

# EXPLORING DESIGNS OF AUGMENTED REALITY SYSTEMS FOR SHIP BRIDGES IN ARCTIC WATERS

**S Frydenberg, K Nordby** and **JO Eikenes,** The Oslo School of Architecture and Design, Norway

## SUMMARY

It is critical for mariners to maintain awareness of what is happening outside the ship. However, an increasing number of bridge systems force users to switch rapidly between an outside view and the screens inside. Augmented reality (AR) technologies may solve these problems by overlaying the physical world with digital content such as graphics and audio. Designing AR systems is a new and complex design space for interaction designers as it requires an extensive understanding of the users' context and how the technology applies to that context. Understanding the real-world implications of rapidly shifting contextual factors is essential for designing systems that support operators' situational awareness. To investigate which situational premises affect the design of AR systems, we have conducted two early-phase field studies using a broad, multifaceted approach. We present our findings and discuss how the resulting insights may be relevant for building a framework for AR design.

## 1. INTRODUCTION

Today, mariners on a ship bridge have to exert great efforts to alternate their focus between the separate interfaces on the bridge in order to achieve situational awareness (SA) [1]. At the same time, their perceptual awareness of what is happening outside the ship needs to be maintained, which constitutes a crucial aspect of the demand on the mariners during operations. However, ship bridge consoles consisting of fragmented and detached systems force mariners to shift their attention (in highly inexpedient ways) between the separate systems interfaces on the inside of the ship bridge and what is happening on the outside.

Emerging technologies, such as augmented reality (AR), may provide new ways of designing user interfaces for ship bridges that meet the unique needs of mariners: to synchronise their personal experience of control with their overall situational awareness, both inside and outside of the vessel [2]. By mixing their perception of the real world with graphical and auditory overlays representing key information, mariners may be able to concentrate their focus on handling a situation to a greater extent. As shown in the aviation industry, a well-functioning mixed reality head-mounted display can have a major impact on workplaces where SA is essential [3,4]. It is likely that AR could function as an expert support system for navigators on ship bridges in the future [5].

Designing AR systems for ship bridges is challenging for interaction designers, as AR introduces new levels of complexity to the design and the use situation. We consider a system complex if, in its entirety, it contains several more diverse features than each individual part contains; this complexity is due to properties such as diversity, interrelations and adaptivity [6]. The dynamic aspects of *environment* and *context* constitute constantly changing key parameters in AR systems. These aspects make the cause-and-effect-relationship of these systems difficult for designers to comprehend – and to account for in the design.

In order to enable the design of future AR-supported systems, there is a need to better understand the possibilities and constraints of designing for AR in a maritime context. To contribute to this area of knowledge, we report on research exploring the human-centred design of AR systems to support SA and decision making for ship bridge crews on Arctic-bound vessels. In this paper, we present our findings and discuss our own experiences from two field studies conducted in Arctic waters to inform the design process of AR. Based on data from the two field studies, the authors' personal experiences and the analysis. These data are implemented to further the design process.

This article reports research that is a part of an EU project, 'Safe Maritime Operations under Extreme Conditions: The Arctic Case' (SEDNA), which seeks to develop an innovative and risk-based approach to safe Arctic navigation, ship design and operations [7].

## 2. BACKGROUND

Navigators on modern ships work in technologically advanced environments. They need an extensive understanding of bridge systems in addition to navigation skills [2]. Information can be presented in misleading ways in such integrated and networked bridge systems, leading to human errors if the information is not continuously visually compared with the ship's surroundings [2]. In order to correct such errors, it is important for the navigator to frequently check all systems or sensors, such as the radar, to take cross bearings [8] and to maintain a good visual perception of what is happening outside the bridge (through the windows).

Hareide et al. (2018) found that the navigators had insufficient head-up time when navigating. The authors argue that the navigators should address their attention 'most of the time to the outside of the vessel, controlling and comparing the position of the vessel towards the navigation system' [8]. Such problems might be solved by capturing parts of the (or the entire) user interface of the bridge through AR-glasses; then, navigators could, on demand, combine their visual perception with key data from the navigation systems close to the area of interest (AOI) outside the window.

AR is part of a continuum of technologies often called mixed reality [9]. Our work addresses multiple variations of AR technology, as shown in Figure 1. However, our main focus is on AR supported by transparent head-mounted displays, optically superimposing virtual images onto the physical world.

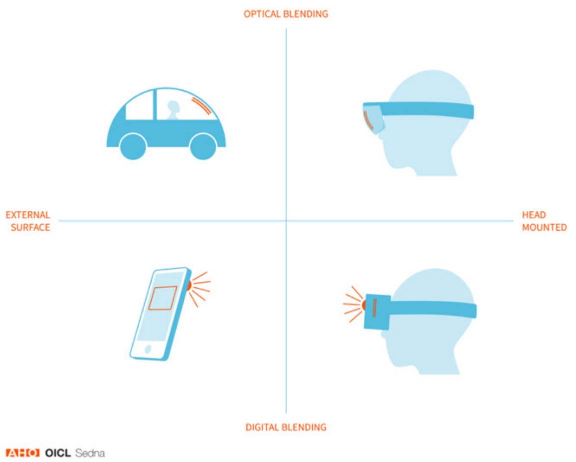



Figure 1: Matrix presenting categorisations of AR as external-surface versus head-mounted and optical versus digital blending.

There has been a steady increase in the number of available head-mounted AR and mixed reality systems on the market in recent years, such as Microsoft HoloLens and Meta 2. Although few of these devices can be realistically implemented to support ship bridge activities in their current versions, they offer good reasons to investigate AR technology as a useful interaction platform for mariners in the near future. Several research projects have looked into how AR can meet ship bridge navigators' need for SA to prevent human error and shipping accidents [5,10–13].

To design interfaces that support a user's SA in safety-critical operating systems is a challenge. According to a study of 100 marine casualties published by the U.S. National Transport Safety Board, poor design of equipment partly caused one third of the accidents [14]. User interfaces designed to integrate with the real world could improve this situation at sea. Improvements may be related to reducing head-down time, aiding the user's ability to directly relate information to their surroundings and superimposing expected ship trajectories onto the physical world. However, aiming at improving a navigator's ability to handle highly variable working situations through design implies designing for *situated interaction* between the navigator and the system. Such a system needs to interpret the user's needs according to the situation they are in, accordingly offering various possibilities for interaction with the system.

Research on collisions suggests that users need visual clues of an impending collision or grounding. A real-world view of the seascape could be augmented using AR goggles, which could work as a feasible method of enhancing SA by reducing head-down time [5]. According to studies from the Naval Academy on the use of AR glasses to provide standard information (e.g. direction, pace, designated distance, bearing, and turn information) in a seascape view during high-speed navigation on littoral waters, eye tracking is a useful method for collecting user requirements [11,12,15].

Designing for AR is not only about designing information according to predefined user requirements but is also about understanding the requirements embedded in a given, yet unpredictable, context. AR interfaces are far more integrated into the user's surroundings than traditional interfaces are. In the development of AR applications for ship bridges, some researchers claim that AR experiments must wait until our understanding of 'what' and 'how' is fully clarified [13]. However, we suggest that an explorative and opportunistic approach will take us further and help us understand the premises of design for AR by iteratively investigating it from many angles. As researchers and designers, we will never fully understand, or be able to map, all situations. Therefore, an important part of our approach is to define scenarios upon which we can base our design decisions. We also propose develop the research in this area as an iterative process of building knowledge, where the interrelated aspects we design for – users, context and technology – are investigated in parallel.

## 3. APPROACH

The aims of the two field studies were threefold; first, we aimed to investigate the premises and possibilities for designing AR systems to be used by ship bridge crews in different scenarios. Second, we aimed to familiarise ourselves with the context and environment of ship bridges in general and during operations in Arctic conditions, specifically. Third, we aimed to test and evaluate a broad set of methods to identify how interaction designers can approach and define the new and complex design space of AR for ship bridges in the field. These aims were carried out by drawing on the *design-driven field research* [16] model (Figure 2) consisting of three related focus areas – data mapping, experiencing life at sea and design reflection – and the field study processes described in *Implementing Field Research in Ship Design* [17].

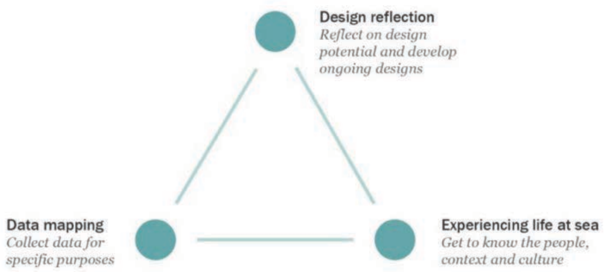



Figure 2: Model for *design-driven field research* developed in the project Ulstein Bridge Concept [16].

The first field study team consisted of a PhD fellow in interaction design, a research assistant and a master's student in industrial design. They conducted the field study for fourteen days on a Norwegian coast guard ship on a research expedition to the West Ice. The research focused on identifying the tasks, the systems used to do these tasks, and the workflows of the bridge crew in selected scenarios. Further, they mapped the physical environment of the bridge and investigated how varying conditions, such as movement and light, affected the needs for, and abilities to handle, system information.

The second field study involved two designer-researchers from the Oslo School of Architecture and Design (AHO) and three researchers from the HALPIN Centre on one of the Swedish Maritime Administration's icebreakers that operates in the Bay of Bothnia. This field study focused on testing current AR equipment and uncovering premises and possibilities for designing AR solutions for different scenarios.

### 3.1 DATA COLLECTION

We used participatory observation as an approach to familiarise ourselves with the context of the vessel and to gain insight into the working situation [18]. We conducted short informal interviews, participated in the day-to-day life of the crew, observed the work on the bridge and initiated group discussions about user needs and ideas to meet these [18]. In order to better understand the operations, we supplemented our observation of navigation in dense ice on the West Ice expedition by the eye-tracking device Tobii Pro Glasses 2 [19]. Recordings were conducted according to normal watch procedures while manoeuvring in dense ice from the bridge wing console.

In both field studies, the bridge environments were documented and mapped as plan diagrams to display the organisation of working stations and the working flow of the actors between them. The actors' movements during different scenarios have significant implications for AR as the surroundings, the field of view and other possible conditions change.

On the West Ice expedition, comprehensive documentation of all consoles on the bridge was carried out to achieve an understanding of the totality of the bridge systems and the current working situation. The implications for AR rely on existing information displays and the possibilities for using suitable areas to embed AR within existing environments.

### 3.2 AR CONCEPT TESTING

A number of tests were conducted on both field studies to observe and evaluate how graphical content and its placement in the bridge environment worked in various environmental conditions in terms of light and movement. The overall aim of these tests was to investigate premises for designing AR to be used on a ship's bridge. On the expedition to the West Ice, we brought Microsoft HoloLens AR glasses to test simple mock-ups and applications. We brought Meta 2 AR glasses with us on the field study to the Bay of Bothnia in order to carry out specific graphical tests. Both HoloLens and Meta 2 allow users to see and hear graphics and audio overlaid on top of the physical world. A virtual reality (VR) scene driven by the Samsung Odyssey VR headset that showed an existing bridge design concept was tested by the crew. An iPhone combined with AR markers was used for testing ideas in context. In addition, a portable mini projector and techniques such as paper prototyping and photoshopping were used to simulate AR in a ship bridge environment to explore its different aspects. The AR tests conducted during the field trips were documented in a test log. Several ideas were prototyped on board based on iterative feedback from the crew.

### 3.3 ANALYSIS

After the field studies, we analysed the data from different categories, carried out a collective analysis and compared our findings during workshops following the methods laid out in [17]. The field studies were documented in two reports that were shared between internal (at AHO) and external project members. The reports were also shared with the crew members on the vessels. External domain experts have verified the content of the documentation in the coast guard vessel report.

The data gathered in the field were used to define and develop specific operational scenarios. We identified and developed the chosen scenarios in consultation with the two ships' bridge crews. After the field studies, the data were analysed and evaluated in team workshops. Further, the scenarios were refined and presented to domain experts as well as the ships' bridge crews from the field studies for verification. We developed a total of ten different scenarios: inshore navigation, offshore navigation, navigation in dense ice, helicopter operation, sea bear (small boat) operation, rescue operation (in which the rescue ship is stuck in ice), escort operation, parking operation, vessel handover and tugboat operation. The aim was to achieve a broader understanding of occurrences in the chosen scenarios, of the actors and their roles, of the bridge functions used and of the communication needs between actors. Scenario mapping is used as a starting point for designing AR concepts.

## 4. RESULTS

We have divided our main findings of the study into three categories: 1) the technical challenges of using current AR technology on a ship's bridge, 2) premises for the placement and appearance of visual AR and 3) example AR concepts based on scenario observations.

### 4.1 TECHNICAL CHALLENGES OF USING CURRENT AR TECHNOLOGY ON A BRIDGE

It is important to test AR technology in real conditions in order to better understand the inherent limitations and opportunities of the technology for design purposes. We do expect the technology to improve over time; however, many of the issues we find now, such as contrast and transparency, will most likely persist in future generations of hardware. In the following section, we describe the challenges of using current technologies in maritime conditions.

#### 4.1 (a) Environment Mapping

The current generation of AR headsets has sensors that scan a user's physical environment in order to generate a 3D map. This map is used as a foundation for identifying users' place in 3D space and to allow 3D graphics to be positioned in direct relation to the real world. However, in our tests of Microsoft HoloLens and Meta 2 in the field, we experienced significant tracking problems on the ships' bridges. Both headsets demonstrated problems while mapping both internal and external environments, probably because of the optical difficulties entailed in the environment (i.e. large windows and varying light conditions).

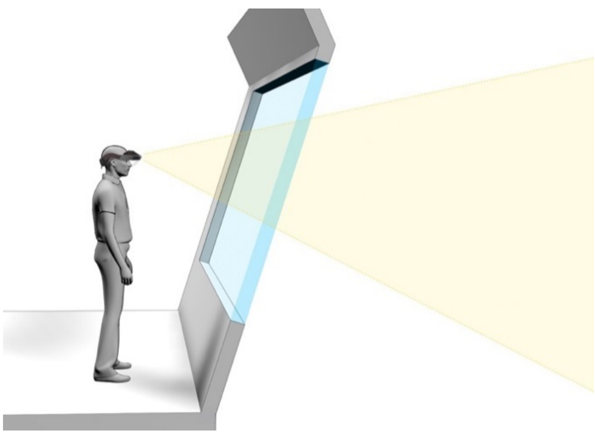


Figure 3: Headsets where only forward-facing tracking cameras are used might not capture any objects on the bridge when the user is standing close to a window, resulting in poor tracking.

The design of good AR systems depends on good tracking in order to fix graphics to internal surfaces, such as panels, windows and consoles, and to pin graphics to external objects, such as other vessels, or to surfaces, such as that of the ocean, that of ice or the horizon. Neither Meta 2 nor the HoloLens managed to offer consistent environmental tracking to support their use in SA scenarios. This is a problem that needs to be solved if these devices are to be used in maritime conditions.

#### 4.1 (b) Contrast and Light Conditions

The differences in ambient light between inside the bridge and outside the vessel are extreme during daytime, especially in ice-filled waters, due to sun reflections. The eye needs time to adjust to the dark areas inside the bridge and the light areas outside. This is a general problem ship bridge crews have to handle, and it is often met by wearing sunglasses or using sun blinds on the windows. During our field study tests, we noted significant visibility problems with the AR devices in terms of displaying graphics onto very light areas (e.g. outside the window during the day) due to the AR devices' combinations of real visual perception and graphics.

At night time, dawn, dusk or in dark weather conditions, current AR devices can display graphics sufficiently on the surface of a window and beyond it without further modifications. In daytime, there is a need for technological improvement for AR glasses that combine real perceptual vision with graphics, such as Microsoft HoloLens and Meta 2.

Differences in light conditions affect how we design AR interfaces. User interface colour schemes need to be adapted so as to offer optimal readability against shifting backgrounds (Figure 4). These problems with light conditions can be avoided using digital blending, where users view the world as a blend of virtual information and digital video of the real world. Such AR solutions can reduce extreme brightness before combining live footage with augmented graphics. Such digital blending is common in mobile phone applications.

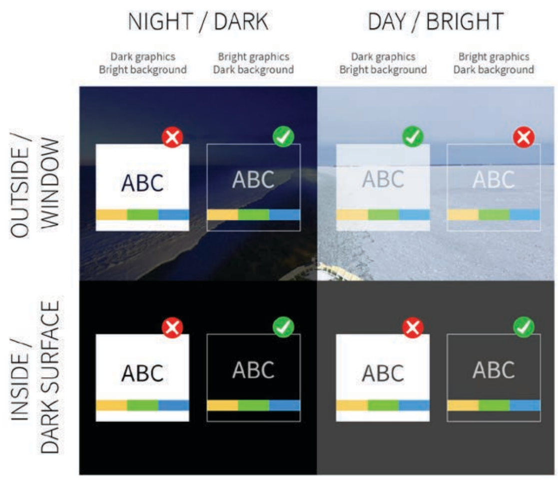



Figure 4: An early schema proposing how colours, fonts and backgrounds should be used in AR in different light conditions without focusing on the visibility problem.

4.1 (c) Movement

*Internal movement*, which we define as a user's way of moving in their environment, must always be thoroughly mapped in all use cases. Internal movement patterns on ship bridges vary greatly according to the size and design of the ship bridge, as well as the operations and the tasks of the crew. In both field studies, the vessel and operation types required a considerable amount of movement from the navigators on the bridges in most situations. Movements included full body, hip, shoulder and head rotation on a navigator's own body axis. For designing AR, this implies that a navigator needs to use their natural visual perception to a great extent, viewing their environment from many angles to continuously maintain SA; thus, graphics must support this need by careful integration of SA support that does not disturb the user's ability to observe the real world.

*External movement*, which we define as motions in the user's environment in which the user is located, constitutes an aspect that significantly affects the design of AR for the maritime domain. A ship's bridge is continually moving, and the degree of motion can increase dramatically in demanding weather conditions. External movement forces the crew to focus on keeping their bodies in balance by trying to equalise their weight through internal movement, stay close to handrails and use their visual perception to orientate themselves. This means that the AR system must be able to support a wide range of movement conditions, from calm to demanding. This adds complexity to how we overlay graphics in the real-world view as well as how users will interact with the AR system. There will most likely be a need to design interfaces that can adapt to various use situations, as well as offering users multiple modes of interaction [20].

In the West Ice field study, we experienced a wide range of ship motions, from no waves to storm conditions. We found that using AR while the ship was in heavy motion was difficult using current technologies. We tested the equipment ourselves in different conditions and found it difficult to locate ourselves and balance our bodies while using AR glasses.

The occurrence and degree of nausea is highly individual and might be reduced with experience at sea. However, we argue that AR systems must be designed with these concerns as important test parameters to develop guidelines. Therefore, the combination of external and internal movements must be considered an important area for further research.

4.2 PLACEMENT AND APPEARANCE OF VISUAL AR (GRAPHICS)

AR graphics can be placed in a user's surroundings in endless ways. We define three types of placement used to categorise design concepts: affixed to the body, affixed inside the bridge and affixed outside the bridge. Investigations of placement and appearance of AR graphics in field studies, for all three categories, is highly dependent on the physical bridge design, such as the size and placement of the windows and the layout of the bridge consoles. Since these factors may vary between vessels to a great extent, they should be considered important aspects to examine in the AR design from case to case. However, we suggest that overall guidelines can be developed in the framework for AR design for placement and appearance of AR graphics according to generalisable factors, such as tasks, movement and SA support. To gain an initial understanding of this, we present selected areas for placement and suggest aspects of appearance to be tested further.

4.2 (a) Placement: Fixed to a Body Sphere

AR Graphics can be affixed to a predefined sphere around the user, which is locked to their head, shoulder or hip movement. The size of the sphere defines the distance between the user's eyes and the graphics. The graphics will follow the user's movements, unlike graphics that are fixed to surfaces or points in the environment. Fixing graphics to a body sphere requires no environment tracking, whereas graphics fixed to the inside or outside of a bridge rely on the AR system's tracking of the surroundings to make a functioning projection.

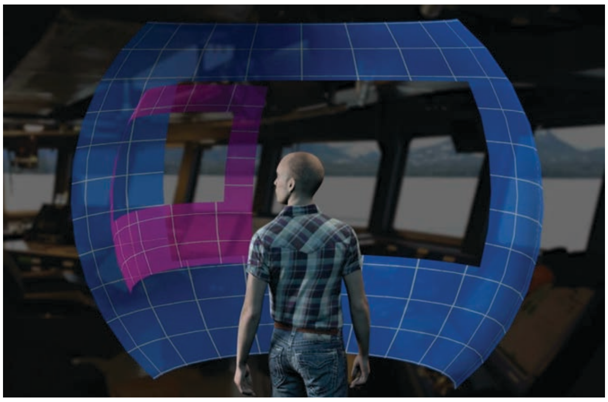


Figure 5: Representation of body spheres for fixing AR content divided into two categories: head-locked content and shoulder-locked content.

In the field studies, most of the premade AR test files we tested on board had graphics affixed to a body sphere. The users experienced annoyance during many of these tests, as the they had to switch their focus between the graphics and the moving environment, rather than looking at graphics embedded in the environment. This was especially evident when the users moved around and when the environment was moving. This experience can be compared with having a stain on one's eye. When the vessel is moving, the body relies strongly on visual perception to maintain balance, which forces the user to focus on the environment, so the stain-effect increases.

Based on these experiences, we suggest that the majority of graphics should be pinned (fixed) to points or surfaces inside the bridge environment or beyond it (to the outside).

4.2 (b) Placement: Fixed to the Inside of the Bridge

Because of glare and the high light contrast on the bridge during daytime, surfaces on the inside of the bridge provide better opportunities for achieving clear graphics than do those on the outside. Many bridges contain areas close to the windows that would be suitable for AR placement, such as panels below and above the windows, the window mullions, and unused surfaces on the consoles. These areas should be considered suitable for overlaying AR graphics containing a larger amount of information since the graphics will not interfere with other important visual information.

Placement on surfaces inside the bridge maintains the existing user situation of switching between information that is relatively close to the eye (1–5 meters) and what is happening outside the vessel, which is relatively far away from the eye (10–∞ meters).

4.2 (c) Placement: Fixed to the Outside of the Bridge

Outside placement of AR graphics could be suitable for a number of AR design concepts that have been evaluated as potentially useful solutions by the bridge crew. Examples are overlaying AR graphics of AIS information pinned to other vessels (Figure 9), projecting key information onto the surface of ice or water during high-intensity operations (Figure 8) or projecting data about ice conditions and leads on the ice, which may support tactical navigation in dense ice (Figure 8).

Placement outside the bridge can be divided into area categories, such as the following:

- On an object (e.g. a vessel, a floating object such as a container or an onshore [or on ice] object such as a polar bear)
- Above the horizon
- On the ocean surface
- On the outside of the vessel (e.g. outside windows, beside the bow or on deck)

Information projected onto the outside of the vessel, close to the windows, is exemplified in Figure 6, where widgets containing key information are displayed outside the windows as the navigator is manoeuvring through dense ice.


Figure 6: Placement in the air outside the window.

By bringing key information closer to perceptual information while looking outside the window, the head-down time of the navigator may be reduced. This implies that if the layout of key information is cleverly designed in order to facilitate a dual information stream, referring to both perceptual and digital information, it could potentially strengthen the navigator's SA.

4.3 DEVELOPMENT OF AR CONCEPTS

As part of the field studies, we developed many concepts on the ship while communicating with the crew. Conducting design conceptualisation in the field is important because it allows us to explore opportunities within the full context, including the participation and comments of the ship's crew [21]. In the following sections, we present two examples of concepts generated at sea that were subsequently visualised in the lab.

4.3 (a) Problem during Navigation in Dense Ice

Navigation in dense ice requires the ship to rupture hard surfaces of ice and manoeuvre between floes. Even though icebreaker vessels can break relatively thick ice, the navigator has to pay close attention when monitoring the ice conditions outside the window in order to manoeuvre safely and efficiently. At the same time, monitoring key information from the bridge systems, such as speed, heading, and machine power, is also necessary. To constantly switch focus between several AOIs inside the bridge and the ice outside makes it difficult for the navigator to maintain good SA. This is due to several factors, including the differing focus distances and light conditions between inside and outside, the cognitive workload required to align and compare several types of data, and the constant need to interpret one's visual perception.

In our field studies, the navigators found it difficult to fully understand the implications of important navigational information, such as radar images of ice or *no-go zones*, from the bridge systems in relation to the real world outside. They expressed a need to better connect information from applications, such as Electronic Chart Display and Information System (ECDIS) and radar, with the outside view.

Based on this need, we present a design concept in Figure 7 where geographical and navigational information is presented as a transparent layer on top of the ocean surface. The figure indicates the no-go zones, the heading and the estimated path of the ship.

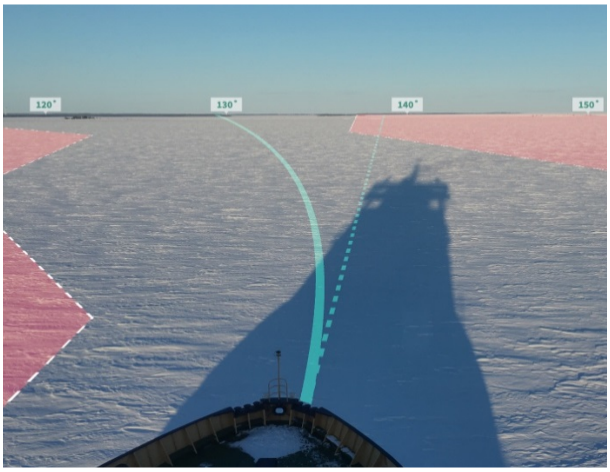


Figure 7: Design sketch with graphics placed on top of a photo, illustrating what the AR view could look like when geographical and navigational information is overlaid on the ocean surface.

We discussed early sketches of this concept with both crews during the field studies, and they considered this concept useful for tactical planning of routes and navigating in closed waters, especially during conditions with poor visibility, such as due to darkness or fog. This concept was originally suggested by the navigators in one of the field studies as a way to help less experienced members of the ship's bridge crew sail in Arctic waters, as this design can supply the user with information about ice conditions, for instance, by implementing information from drone photos into the AR overlay projected onto the real world, such as on the ice surface.

A solution to address other needs in this scenario is given in Figure 8. This solution involves placing small information widgets (e.g. for machine power or heading information) close to the navigator's AOIs near the bow of the ship.

Figure 8: AR widgets representing selected information from the Conning system placed onto the ice.

The concept shown in Figure 8 was informed by the eye-tracking data we collected, showing that users switched rapidly between looking at key information on the inside and at the ice outside. The feedback from the crew was positive regarding earlier sketches of this concept as it may reduce the problem of constant alteration of one's line of sight and mental focus. It might also make comparison of data easier for the navigator, as the information can be represented and placed in a more suitable location.

4.3 (b) Problem during Escort Operation

This scenario describes an on-duty icebreaker that escorts another ship. The ice breaker creates a channel in the ice through which the other vessel can follow. This scenario presents challenges for navigators, such as monitoring the speed and distance between the ships.

In Figure 9, we present a design concept that meets the needs of the navigator by connecting labels or information feeds to the icebreaker vessel, enabling the connection of the real-world view with key information needed in this specific situation.

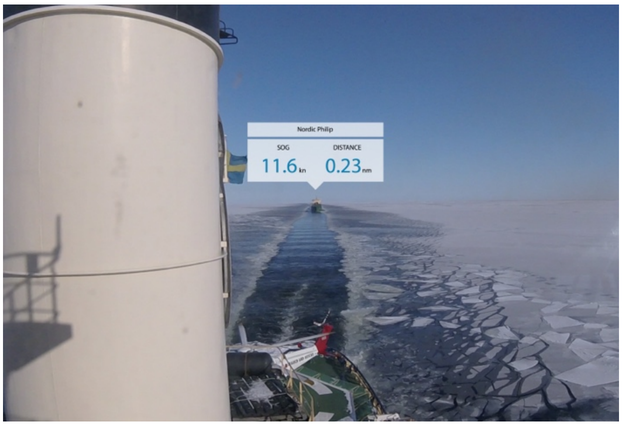



Figure 9: Design concept made by placing graphics on top of an image to show how key information can be connected to another object.

We showed early sketches of this concept (Figure 9) to the crew in one of the field studies. They considered the idea of connecting information labels to objects in the external environment as a useful one. Especially during operations that demand a certain degree of control over other vessels, such as tugboat, escort and sea bear operations, this virtual labelling could support the navigators' SA and allow them to achieve a better overview of the situation.

In other conditions it might be beneficial to have different representations of the same type of information, for example during complete darkness, or if the view is obstructed by large objects. In the design concept in Figure 10, key information is displayed on one of the dark panels below the window in order to keep the information close to the vessel(s) outside (which now can only be perceptually identified by lanterns). In addition, the icebreaker vessel's own key information is placed next to the escorted ship's information to make comparisons easy.


Figure 10: Design concept to indicate a ship's own relation to other ships by displaying information on a dark panel below the window. Prototyped by projecting graphics onto surfaces on the bridge using a portable mini-projector.

The development of scenarios was central to our concept development. The ten scenarios provided us with a better spatial and temporal understanding of selected situations where conditions, circumstances and needs were defined. The scenarios enabled us to structure ideas and develop concepts according to specific frames. Concepts staged within a scenario can, in some cases, be easier to communicate than abstract or general concepts because both experts and users are familiar with the scenario, which defines clearer parameters from which to evaluate the concept.

## 5. DISCUSSION

The two field studies have given us a wider understanding of the design problem; we collected many types of data during the studies that we have built upon in the further design process. We have presented the results after analysing these data and will discuss their implications for further research.

The overall results of the two field trips have shown that AR has the potential to be used as a rich interaction medium for navigators on the bridge of a ship. Through these field studies, we found that AR can be used to display a broad range of information necessary when operating a bridge. We suggest that AR has the potential to be a support system that can be combined with a physical bridge or even fully integrated with a complete bridge operation system.

Our research indicates that AR has the potential to convey many types of information. Research on AR in the maritime domain has focused on SA support [3,4]. However, our research is focused on the *interaction design* of AR. Our results point to a broader range of AR concepts than have been described in previous research. We suggest that a number of applications, possibly the whole integrated bridge system, may be mediated through AR glasses. Our exploration of new ways to present key information according to specific scenarios demonstrate that AR has great potential for presenting information in new and more situated ways.

The scenarios we have developed enabled us to structure design concepts and demonstrators according to realistic situations and defined needs. The selected scenarios also strengthen the reliability of communications with outside actors. Possible disadvantages of focusing on selected scenarios include the lack of total needs among the crew members in all situations. It might be problematic to transfer abstract concepts that have been developed for specific scenarios. Finally, the selected scenarios could be too narrowly defined as it might not be possible to capture all conditions in a given scenario that could affect the users' needs. This should especially be considered when working with a ship's bridge crew as a use case, as it is a context exposed to highly varying conditions.

We have described some of the technical challenges of using current AR technology on a ship's bridge, including environmental mapping, movement, and contrasts and light conditions. Our findings clearly show that the immaturity of the current technology and equipment causes extensive problems when these are used on a ship's bridge. There were problems in testing all prototypes, which partly led the research to focus on the aspects that could be tested. However, we have tried to look past current technical challenges of today, and rather used design techniques such as manipulation and staging for sketching and testing ideas. We suggest that the user's needs should be considered to understand how the technology ought to work, and this can be defined through a communicable design concept.

Our work suggests that designing AR systems for ship bridges is a complex design problem that needs to be approached iteratively from multiple angles. Utilising a range of methods during field studies has proven useful for investigating the conditions for AR described in this paper, which can be used in building a conceptual framework for AR. We further suggest that common guidelines are needed for user interfaces and interactions with all bridge applications in order to move towards an integrated AR bridge system.

## 6. CONCLUSION

In this paper, we presented findings from two field studies conducted on icebreakers with the aim of exploring premises and possibilities for designing AR systems for Arctic-bound ship bridges.

Our study shows that designing AR applications for the maritime domain involves specific challenges, such as ship motion, light conditions and a large variation in user movements and tasks. Further, we found that the current state-of-the-art AR hardware does not function optionally in a ship bridge environment with its variable light and large reflective windowpanes. However, we also found many opportunities for supporting ship bridge crews' work using AR technology.

Based on our experiences, we argue that designing AR for ship bridges is challenging; however, if the technical challenges can be solved, AR may improve maritime operations in the future.

## 7. ACKNOWLEDGEMENTS

The research presented in this paper was funded by the EU project SEDNA. Thanks to Nicholas Stevens for contributing with ideas, observations and technical skills. Thanks to the SEDNA team for their participation in the field studies, their input and their contributions to furthering the design processes. Thanks to Odd Sveinung Hareide and Robert Lynch for organising the field studies, and Hareide for an expert evaluation of one field study report. Thanks to NTNU Ålesund for lending eye-tracking equipment. Special thanks to the Norwegian Coastguard, the KV Svalbard and crew, The Swedish Maritime Administration, the Icebreaker Atle and crew.

## 8. REFERENCES

1. LÜTZHÖFT, M., NYCE, J., 'Integration Work on the Ship's Bridge', *Journal of Maritime Research*, 2008.
2. HAREIDE, O.S., OSTNES, R., MJELDE, F.V., 'Understanding the Eye of the Navigator', *European Navigation Conference Proceedings*, 2016.
3. MELZER, J., 'Head-Mounted Displays', In: SPITZER, C., FERRELL, U., FERRELL, T., editors, *Digital Avionics Handbook,* 3rd edition, Taylor & Francis Ltd, 2017.
4. RASH, C. E., 'The Potential of an Interactive HMD Helmet-Mounted Display' US Army Aeromedical Research Laboratory, 2009.
5. BALDAUF, M., PROCEE, S., 'Augmented Reality in Ships Bridge Operation', *ISIS 2014 – International Symposium Information on Ships*, 2014.
6. LURÅS, S., LÜTZHÖFT, M., SEVALDSON, B., 'Meeting the Complex and Unfamiliar: Lessons from Design in the Offshore Industry', *International Journal of Design*, 2015.
7. SEDNA-project.eu [cited 2017 Nov 28]. Available from: https://sedna-project.eu/.
8. HAREIDE, O.S., 'Improving Passage Information Management for the Modern Navigator', *IALA 2018 Korea*, 2018.
9. SILVA, A., SUTKO, D.M., *Digital Cityscapes: Merging Digital and Urban Playspaces*, 1st printing edition, New York: Peter Lang Inc., International Academic Publishers, 2009.
10. BENEDICT, K., KIRCHHOFF, M., GLUCH, M., FISCHER, S., SCHAUB, M., BALDAUF, M., 'Simulation-Augmented Methods for Safe and Efficient Manoeuvres in Harbour Areas', *International Journal on Marine Navigation and Safety of Sea Transportation*, 2016.
11. HAREIDE, O.S., MJELDE, F.V., GLOMSVOLL, O., OSTNES, R., 'Developing a High-Speed Craft Route Monitor Window', In: *Augmented Cognition Enhancing Cognition and Behavior in Complex Human Environments*, Cham: Springer, 2017
12. HAREIDE, O.S., OSTNES, R., 'Scan Pattern for the Maritime Navigator', *International Journal on Marine Navigation and Safety of Sea Transportation*, 2017.
13. PROCEE, S., BORST, C., VAN PAASSEN, M.M., MULDER, M., 'Toward Functional Augmented Reality in Marine Navigation: A Cognitive Work Analysis', *16th Conference on Computer and IT Applications in the Maritime Industries*, 2017.

14. ROWLEY, I., WILLIAMS, R., BARNETT, M., PECKAN, C., GATFIELD, D., NORTHCOTT, L., et al. *Development of Guidance for the Mitigation of Human Error in Automated Ship-Borne Maritime Systems*, Swansea: Maritime and Coastguard Agency, 2006.
15. HAREIDE, O.S., OSTNES, R., 'Maritime Usability Study by Analysing Eye Tracking Data', *The Journal of Navigation*, 2017.
16. LURÅS, S., NORDBY, K., 'Field Studies Informing Ship's Bridge Design at the Ocean Industries Concept Lab', *Human Factors in Ship Design and Operation: 26–27 February 2014,* London, UK: Royal Institution of Naval Architects, 2014.
17. GERNEZ, E., NORDBY, K., 'Implementing Field Research in Ship Design', *In Press*.
18. DEWALT, K.M., DEWALT, B.R., *Participant Observation: A Guide for Fieldworkers*, Rowman Altamira, 2011.
19. Tobii Pro Glasses 2 Wearable Eye Tracker 2015 [cited 2018 May 14]. Available from: https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/.
20. NORDBY, K., LURÅS, S., 'Multimodal Interaction for Marine Workplaces Used as Strategy to Limit Effect of Situational Impairment in Demanding Maritime Operations', *International Conference on Marine Design 2015, 2–3 September 2015,* London, UK, 2015.
21. LURÅS, S., 'Layered Scenario Mapping: A Multidimensional Mapping Technique for Collaborative Design', *CoDesign*, 2016.

## 9. AUTHORS BIOGRAPHY

**Synne Frydenberg** has been a PhD fellow since 2017 at The Oslo School of Architecture and Design. She also works part time as a design researcher within the SEDNA project. Her research interests lie in designing for situated interaction in complex professional settings, such as a ship's bridge. Before starting her PhD, she worked six years as an interaction designer in the Norwegian design consultancy Making Waves and in the digital department of a Norwegian publishing house, Gyldendal.

**Kjetil Nordby** (PhD) is an associate professor at The Oslo School of Architecture and Design. He is a research manager for Ocean Industries Concept Lab and the project leader of the OpenBridge project. His previous experience includes interaction design, industrial design, design management and research management within ocean industries.

**Jon Olav Eikenes** (PhD) is a designer and researcher at The Oslo School of Architecture and Design. He works part time as a design researcher within the SEDNA project. His previous experience includes research on visualisation and animation in interfaces. He has worked several years as a designer and contributed to the design of several products for ship bridges.

# PUBLICATION 2

Frydenberg, S., Nordby, K., & Eikenes, J. O. H. (2019). Serendipity in the field. Facilitating serendipity in design-driven field studies on ship bridges. The Design Journal, 22(S1), 1899–1912. https://doi.org/10.1080/14606925.2019.1594948

# **Serendipity in the Field.** Facilitating serendipity in design-driven field studies on ship bridges

Synne Frydenberg[a], Jon Olav Eikenes[b], Kjetil Nordby[c]

[abc]The Oslo School of Architecture and Design
*Corresponding author e-mail: synne.g.frydenberg@aho.no

**Abstract:** Field research requires openness to unforeseen insights and opportunities, especially when designing for complex and dynamic workplaces, such as a ship bridge. In this paper, we investigate how serendipitous outcomes may be facilitated in design-driven field research. We present a case study of two field research trips onboard Arctic-going vessels, during which we investigated the premises of designing augmented reality (AR) systems for navigators. We describe how an explorative and opportunistic mixed-methods approach facilitated serendipity and analyse which specific aspects led to serendipitous outcomes in three examples. Last, we discuss how practical support for designers and design researchers conducting design-driven field research can be developed and suggest how strategies to employ approaches that facilitate serendipity can increase the likelihood and awareness of serendipitous outcomes.

**Keywords:** Design-driven field research, Ship bridges, Serendipity, Maritime design, Augmented reality

## 1. Introduction

Design for user experience is currently expanding into new, more complex domains in which safety is critical, such as ship bridge design (Lurås, Lützhöft, & Sevaldson, 2015). Since most designers and researchers are unfamiliar with ship bridges, *design-driven field research* has been proposed as a method to acquire the experience and knowledge needed to develop designs for the maritime domain (Lurås & Nordby, 2014).

When the aim of a field study is to explore and generate new ideas and solutions, designers are hoping for unexpected insights and ideas. The context, situations and findings of the field study are likely to present designers with questions, problems and design possibilities they could not envision before the field study. Planning specifically how such a field study will proceed is often impossible. More importantly, defining the outputs of such a field study too concretely before entering the field may result in overly narrow data collection.

*Serendipity* refers to approaches and activities that allow one to discover findings that are unexpected, fortunate and valuable (Carr, 2015; Halvorsen, 2016; Lunenfelt, 2003). But how can designers facilitate serendipity in the field? In this paper, we investigate how an approach that takes serendipity into account can be valuable in design-driven field research, especially when exploring new technological solutions such as augmented reality (AR).

The EU project Safe Maritime Operations under Extreme Conditions: The Arctic Case (SEDNA) is intended to investigate how the working conditions on ship bridges in the Arctic can be improved, for example, by the use of AR. A ship bridge on an Arctic-going vessel features rapidly changing and unpredictable situations, mainly due to ice and weather conditions (Figure 1).

*Figure 1: Field research in Arctic waters (Photo: SEDNA).*

Navigators need to simultaneously maintain situational awareness of what happens outside the ship and monitor ship bridge systems on consoles inside the ship (Hareide & Ostnes, 2017). AR is an emerging technology that can be used to overlay the physical world with digital content regarding the bridge systems (Frydenberg, Nordby, & Eikenes, 2018). Thus, by using AR technology and head-mounted displays, system information can be integrated with the physical environment and adapted to specific situations and users' needs. Some research has examined how AR can meet navigators' needs for situational awareness in order to decrease human error in shipping accidents (Baldauf & Procee, 2014; Benedict et al., 2016; Hareide et al., 2017; Hareide & Ostnes, 2017; Procee, Borst, van Paassen, & Mulder, 2017; SEDNA-project.eu, 2017). However, it is yet unknown how AR can and should be designed for and used on the bridge, especially in extreme environments such as the Arctic.

In this paper, we present a case study from SEDNA and investigate how design-driven field research can be planned for and conducted to facilitate serendipitous outcomes. This work contributes to the body of knowledge about implementing serendipity in the field. Through two field studies of icebreaker vessels in Arctic waters, we investigate the premises and possibilities for designing AR systems using a broad set of mixed methods and an explorative and opportunistic approach. We analyse three examples from the field studies and describe aspects that led to relevant and unexpected outcomes. Then, we suggest four potential strategies that might support serendipity in the field.

# 2. Background

## 2.0 Serendipity – More than Happy Accidents

There are multiple definitions of the concept of serendipity, including "the art of making an unsought finding" (Rivoal & Salazar, 2013, p. 1) and "the faculty of making happy and unexpected discoveries by accident" (American Heritage Dictionary of the English Language, 2018). Serendipity is not a new concept in academic inquiry; it is part of a systematic sociological method in grounded theory for construction of theories based on gathering and analysis of data that can explain a phenomenon or situation (Strauss & Corbin, 1994), and in the field of anthropology, it is a key characteristic of the ethnographic method (Rivoal & Salazar, 2013).

Developments in the understanding of the phenomenon of serendipity and the theoretical underpinnings of unexpected and positive user experiences have triggered significant interest in digital information environments in recent years (McCay-Peet & Toms, 2017). However, the empirical underpinnings of how to identify a practical construct that could be useful for designers' needs are still poor (Makri, Blandford, Woods, Sharples, & Maxwell, 2014). Scholars exploring serendipity have attempted to capture the concept of serendipity in different ways, including serendipity models (Makri & Blandford, 2012), frameworks (Erdelez, 2005), drivers (McCay-Peet & Toms, 2017), experiences (Makri et al., 2014) or the nature of the phenomenon (Sun, Sharples, & Makri, 2011). Nevertheless, the body of work aiming to understand and conceptualise what contributes to serendipity is still in its infancy (McCay-Peet & Toms, 2017).

A practical example of an attempt to develop support for designers using qualitative methods is an interview study intended to discover how 14 creative professionals self-report the strategies they use to increase the likelihood of serendipity (Makri et al., 2014). The study suggests that such strategies can function as a framework for further exploration.

Because serendipity is interpreted and expressed in different ways in different contexts and fields, it is useful to examine the origin of the word. Reportedly, the word *serendipity* comes from a Persian fairy tale called *The Three Princes of Serendip* (now Sri Lanka). In the story, the three princes are sent into the world by their father, the king, to gain broader experience and wisdom. During their travels, they successfully find a lost camel through happy *accidents* and *sagacity*, that is, by connecting seemingly insignificant elements in such a way that leads to an unexpectedly positive (i.e. serendipitous) outcome (Merton, 2006).

The *accidental* part of serendipity requires designers to respond to opportunities while in the field (Makri et al., 2014). The likelihood of serendipity caused by an accident could be increased by situating the fieldwork within an immersive and unpredictable context. Considering only accidents may lead one to view serendipity as a phenomenon that one has no control over (Rivoal & Salazar, 2013). However, this is an incomplete understanding; it is difficult to achieve serendipity in a research process without considering *sagacity* (Fine & Deegan, 1996). According to Rivoal and Salazar (2013), the skilful synthesis of accidents and sagacity in anthropological research requires that the researcher have 1) sufficient background knowledge, 2) an inquisitive mind, 3) creative thinking and 4) good timing.

## 2.1 A Framework for Analysing Serendipity in Design

In order to develop a lens with which to analyse our design-driven field research on serendipity, we elaborate on the four aspects of serendipity suggested by Rivoal and Salazar (2013).

*Sufficient background knowledge* can be understood as having enough insight to understand what is not immediately obvious. A number of scholars have emphasised the key role of background knowledge in serendipitous discoveries. For example, the French microbiologist and chemist Louis Pasteur (1854) emphasised the importance of preparation before observation: “In the fields of observation chance favours only the prepared mind” (as cited in Vallery-Radot, 1928, p. 76). In other words, serendipity depends on one having a fundamental understanding of the domain, context and material or problem under investigation before the investigation begins. However, Mauss (2009) argued that in order to implement background knowledge in field research, sociological perception is also important: “The young ethnographer embarking upon fieldwork must be aware of what he or she knows already, in order to bring to light what is not yet known” (p. 8). This aspect is referred to as *reflexive interpretation*, and it is a hallmark of the anthropological method (Rivoal & Salazar, 2013) that may be useful for design researchers during the reflection process.

An *inquisitive mind* can be understood as one with sufficient background knowledge that optimistically reacts to unforeseen outcomes in the research. Many great discoveries within the natural sciences derive from this explorative aspect of serendipity, from Alexander Fleming’s discovery of penicillin (Colman, 2006) to the development of Velcro and Viagra (Roberts, 1989). Viewing fieldwork as an iterative and elaborative process in which seemingly irrelevant elements develop into a greater body of knowledge (Crabtree, Rouncefield, & Tolmie, 2012) may support the notion of *building* serendipitous outcomes with sagacity rather than *happening upon* them.

*Creative thinking*, understood broadly as the ability to come up with new ideas, is often credited when serendipity is connected to new inventions (Kingdon, 2012). For example, radical innovations are often linked to the introduction of new technologies, such as AR, which enable designers to create new affordances or meanings through serendipitous exploration (Norman & Verganti, 2014). Creative thinking can be described as “a muscle that you can choose to work out or allow to wither” (Kingdon, 2012, p. 3). The ability to embrace serendipity in design can be compared to the ability to improvise in other creative fields, such as music and theatre, which involves not only the emotional and aesthetic personal characteristics of a person but also tacit knowledge that can be used in interactions with other persons (Alterhaug, 2004, 2010). User experience researchers must view users as humans, meaning that rich data cannot be forced (Nunnally & Farkas, 2016). Improvisational skills and the ability to creatively use unforeseen events or findings may help facilitate conversations with users in which interesting data develops naturally.

*Good timing*—and time—are required for research to facilitate serendipity (Rivoal & Salazar, 2013). The researcher’s *fieldwork demeanour*, which is key for gaining acceptance in the field, should involve respect, empathy and common sense about when people will open up (Crabtree et al., 2012). Good timing can be described as being attentive to when this happens. As opposed to anthropological field research, field research on maritime design generally takes place over shorter periods, which reduces the opportunity to move back and forth between data collection and the final analysis (Lurås et al., 2015). This often results in rather intense fieldwork, as the researcher has little time to digest the information. Nevertheless, setting aside time to document, interpret, reflect and debrief between each data collection session during the field study is necessary to properly document and understand the data (Lurås & Nordby, 2015).

It might not be possible to rigorously plan for serendipity, but it is possible to manipulate the conditions that can lead to serendipitous outcomes (Rivoal & Salazar, 2013). Below, we present a case study through which we analyse how various field research techniques and methods enable serendipitous insights.

# 3. Case: AR design for ship bridges

In this paper, we use two field studies, which were conducted as part of the EU project SEDNA and examine how AR technology might improve navigators' working situations, as a case study to investigate how serendipitous outcomes may be facilitated in design-driven field studies.

AR is a rapidly developing technology (Bonetti, Warnaby, & Quinn, 2018). However, there are few practical guidelines for designers regarding how to explore and design AR systems for complex contexts, such as a ship bridge. Investigation of the parameters and possibilities of designing AR systems for ship bridges requires a certain amount of domain knowledge to understand the demanding, dynamic, high-risk working environment as a whole (Lurås et al., 2015). In addition, the use of AR on the bridge is categorised as a design problem that cannot be divided into two distinct phases—*problem definition* and *problem solution*—in a linear design process (Buchanan, 1992). This type of challenge, which is characterised by a number of issues, including the fact that it is impossible to understand until a solution is developed, is referred to as a *wicked problem* (Rittel & Webber, 1973). One cannot predict which issues and questions will arise from the research process and thus needs to constantly search for new solutions and iteratively redefine the design problem.

To better understand the potential of AR on ship bridges, we conducted two field studies in March 2018 on vessels with ice-breaking capabilities operating in two regions in the Arctic. One study was conducted by three project members onboard a Norwegian coast guard ship on a 14-day marine research expedition to the West Ice (East Greenland). The second study lasted four days and was conducted by two team members in cooperation with three researchers from a co-research institution on one of the Swedish Maritime Administration's icebreakers operating in the Bay of Bothnia.

The purposes of the field studies were to 1) explore the conditions and possibilities for designing AR systems for navigators on a ship's bridge, 2) to investigate how design researchers can methodologically approach the design of AR systems through field studies and 3) to familiarise ourselves with the context and environment of a ship bridge.

We used an explorative and opportunistic mixed-methods approach (Hanington & Martin, 2012; Nunnally & Farkas, 2016) to perform our field study. The approach for carrying out design-driven field research in the maritime domain is based on design ethnography research (Crabtree et al., 2012) and research conducted by the Ocean Industries Concept Lab at the Oslo School of Architecture and Design. This lab developed methods and models such as *design-driven field research* (Lurås & Nordby, 2014, 2015), which features the focus areas *design reflection, data mapping* and *experiencing life at sea*, specifically for the purposes of design and design research (Gernez & Norby, in press; Lurås & Nordby, 2014).

# 4. Enabling serendipity in the field

As we have argued, facilitating serendipity in a design-driven field study requires sufficient background knowledge, an inquisitive mind, creative thinking and good timing. The following section describes how we facilitated serendipity through preparation and careful selection of a method.

## 4.1 Planning for Serendipity

Exploring the design of AR systems for ship bridges in the Arctic was a complex challenge with many unknown aspects. For example, how could we ensure targeted data collection while simultaneously allowing for serendipitous outcomes, and how could we foster sagacity?

Based on the three main aims of the field studies, we acquired as much background knowledge as possible, created a comprehensive field study plan for what we wanted to understand and explore while in the field and prepared a variety of design activities.

Since we cannot predict the unexpected, we did not know in advance which methods would be use useful, realistic or suitable. Building on previous design-driven field studies, we adopted a multifaceted field study methodology that would enable us to be *explorative* (i.e. to explore and discover) and *opportunistic* (i.e. to exploit opportunities). Preparing for the unexpected not only revealed a wide range of possible approaches but also allowed us to internalise information and be mentally prepared for the field.

Our planned research was approved in advance by the Norwegian Centre for Research Data. At the beginning of the trip, we attended an information meeting to explain the purposes and approach of the field research. Then, we obtained written consent from all the involved crew members. For each new and serendipitous use of the collected data, such as the use of eye-tracking recordings for design sketching, we obtained consent again. Comprehensive reports of the collected data and plans for further use of the data were approved by the leaders of each vessel after the trip.

## 4.2 A Mixed-Methods Approach

While performing the field studies, we used a mixed-methods approach consisting of a broad set of standard methods from the fields of design, human–computer interaction (HCI), human factors (HF) and the social sciences. We aimed to continuously conduct reflection in action (Schön, 1984) and so-called *design reflections* (Lurås & Nordby, 2014) in between the planned methods and activities to iterate on design solutions in parallel to data collection. We aimed to exhibit inquisitiveness, creative thinking and correct timing by using and expanding on the methods described above. Finally, we adjusted the activity plan as we gradually achieved more insight and serendipitously uncovered new and significant aspects that needed to be incorporated into the design and research activities.

The following methods were used:

- **Participatory observation** (DeWalt & DeWalt, 2011) was used to conduct semi-structured interviews based on interview guides, informal talks, direct observation of the work on the bridge and collective discussion about users' needs and ideas.
- **Scenario mapping** (Lurås, 2016) was used to systematically gather and present data about a constructed user situation in order to design AR concepts to meet specific needs.
- **Mapping behaviour on the bridge** (Hanington & Martin, 2012) was used to determine the organisation of working stations and the workflow of actors due to the significant implications of where and how visual information can be presented to an AR user.
- **User environment design** (Beyer & Holtzblatt, 1997) was used to document all consoles on the bridge in order to understand the entire bridge system and current working situation.
- **Co-creation** (Sanders & Stappers, 2008) was used to reorganise content and functions with experienced crewmembers in a workshop to achieve more optimal working conditions on the bridge based on their experience. The implications for AR were related to existing information displays and the potential for embedding AR in suitable projection areas within the existing environment.

- **Eye-tracking** (Hareide & Ostnes, 2017) data were collected using Tobii Pro Glasses 2 to determine how long and often the navigator looks at and alternates between different points of interest in different situations.
- **Testing equipment** (Rubin, Chisnell, & Spool, 2008) included AR glasses—Microsoft HoloLens and Meta 2—which allow users to see and hear graphics and audio overlaid on the physical world. A VR headset with a conceptual model of the existing bridge design was tested by the crew. An iPhone was connected to a VR box using AR markers. The overall aim of the test was to explore the parameters for the design of AR ship bridge systems in various environmental conditions with differences of light and movement. Test logs were kept to systematise the AR tests.
- **Development of concepts for AR** (Hanington & Martin, 2012) was performed with techniques such as paper prototyping, Photoshopping and a portable mini projector to simulate AR in the environment and explore the use of AR in this context.
- **Collection of visual data for visualisations** was performed using drones, a 360-degree camera, GoPro cameras and single-lens reflex camera to capture and document various user situations, water and weather conditions and operations.

## 4.3 Data Collection

As shown in Table 1, our field research approach allowed us to collect a broad set of data (more than 2800 images and 350 video recordings) in both targeted and serendipitous ways. This involved data mapping, design reflection and the personal experiences of the design researchers. We summarised and analysed the data after the field trip, shared and discussed insights through workshops with team members and documented the insights in two field study reports validated by domain experts.

*Table 1. Overview of data collected using each method.*

| Method | Data Collected |
|---|---|
| Semi-structured interviews | Notes, audio recordings, photos, videos, sketches |
| Participatory observation | Notes, photos, videos, sketches |
| Scenario mapping | Visual diagrams, notes, photos, videos |
| Mapping behaviour on the bridge | Visual diagrams, notes, photos |
| User environment design and co-creation | Visual schemas, notes, photos, videos, sketches |
| Eye tracking | Eye-tracking record data |
| Testing AR equipment | Notes, photos, videos, test log |
| Development of concepts for AR | Photos, videos, 360-degree photos and videos, drone photos |

Before the field trip, we were not able to anticipate all the kinds of data and insights we would collect and how they would be useful both during and after the field study. For example, the eye-tracking video recordings were used not only to identify the eye-tracking patterns of the navigator, as we expected, but also as background footage that allowed us to sketch new design concepts after the trip.

During the debriefing for the field study, the participants expressed that a significant part of the insights gained in the field studies were due to serendipity, such as being present in particular situations or observing conditions develop differently than expected. They regarded much of this knowledge to be influential for further work as it enables well-founded judgements of designs for the ship bridge environment.

# 5. Examples of serendipitous outcomes

In order to specifically evaluate how serendipity occurred during the field studies, we present and analyse three situations in which we experienced serendipitous outcomes.

## 5.1 Co-creation and Design Intervention

We started by performing participatory observations on the ship's bridge to familiarise ourselves with the bridge, working situation and operations taking place. However, we found that our *background knowledge* was insufficient to understand the complexity of the various operations and working situations.

We thus improvised an unplanned research activity (*creative thinking*) to gain a better overview. This involved fully functional mapping of the ship's bridge with help from the crewmembers on duty. During the mapping process, we received unexpected and relevant insights from the users of the systems regarding optimisation of the console design. To gain deeper knowledge, we asked the users to participate in a co-creation workshop (*inquisitive mind*) to optimise the bridge console design (Figure 2). The users' different personal preferences and needs resulted in various versions of the optimal bridge console.

*Figure 2: Co-creation workshop in which system users helped determine the optimal bridge console (Photo: SEDNA).*

The serendipitous outcomes in this example include an unplanned activity (mapping the current console layout), insights into how the current system fails and succeeds in meeting users' needs in different situations, a set of co-designed concepts for new design solutions and testing and documentation of a new method for performing design-driven field studies.

## 5.2 Transitions as Information-Dense Situations

We conducted a semi-structured interview focusing on task-solving and critical points in what was categorised as a semi-intense situation due to rough ice conditions. The planned interview (Figure 4) provided us with a good overview. We stayed at the same spot after the interview and were accidently able to observe a handover between the current and new watch officers (*good timing*), which involved a two-minute briefing covering the same topics as the interview. However, the description differed in terms of specific references and pointed to different critical points.

In order to understand the dissimilar descriptions, we switched our method and asked the new watch officer if he was willing to use the eye-tracking equipment (Figure 3) we had prepared for another situation (*inquisitive mind* and *creative thinking*). The eye-tracking recordings provided a new perspective on how the watch officer worked during challenging situations.

*Figure 3: The image to the left shows an informal interview with a watch officer by the bridge console, and the image to the right shows our switch of method to eye tracking (Photos: SEDNA).*

The serendipitous outcomes include a new and unexpected perspective on a specific situation, insights into how communication conveying form and content is highly dependent on relationships, and eye-tracking data as an objective observation tool to supplement the data collection.

## 5.3 Contextual Wake-Up Call

We tested how AR graphics fixed to the user's body would be experienced on the bridge during calm conditions. Users evaluated the solutions as useful and satisfactory for the intended purpose. However, on our way back to the mainland, we decided to run another test session during demanding weather conditions with waves to see how movement would affect the AR user's experience (*inquisitive mind* and *good timing*). This time, the users experienced severe problems with the projected graphics; the conditions led to issues such as poor visibility and difficulties related to keeping the body in balance. Several of the test files that had been evaluated as functional earlier were experienced as annoying and contributed to nausea in wavy conditions.

We also conducted the tests on ourselves. We found that predicting the intensity of this effect is difficult, and it is difficult to simulate the effect with AR equipment without being in the actual context and conducting tests over a period of time. We had to be receptive to unexpected insights and be willing to change our perspective on new design concepts, including use of a body sphere to attach most of the AR graphics to surfaces in the physical environment inside or outside out of the bridge (Figure 4).


*Figure 4: Illustration showing a design concept in which graphics are placed outside the window to accommodate the need to fix graphics to the environment instead of a body sphere (Photo: SEDNA).*

In this example, the serendipitous outcomes included new insights into how different situations and conditions affect the usability of AR and enable a new direction for design solutions.

# 6 Discussion

We argue that it is useful to support designers by helping them to build their own approaches enabling serendipity. One way of doing so is to examine cases in which these approaches are used to investigate new design problems, new contexts or new methods. We believe such cases can help designers better identify and react to serendipity in their own practice.

As described in the background section, we believe the phenomenon of serendipity consists of two factors: accidents and sagacity. We consider accidents to be something we cannot control, although we can place ourselves in unpredictable situations for long periods of time to increase the likelihood of serendipitous outcomes (Rivoal & Salazar, 2013). Based on our case study, we suggest that sagacity, also understood as *the perception aspect of serendipity* (McBirnie, 2008), can be enhanced by designers through preparation, implementation and exploration of the four aspects of sagacity (Rivoal & Salazar, 2013): *sufficient background knowledge*, *an inquisitive mind*, *creative thinking* and *good timing*. We used these aspects as lenses to analyse our own experiences of serendipitous outcomes, and next, we discuss how they helped us understand the example in our case study and how we might develop strategies to achieve serendipity in design-driven field research.

One way of developing practical design support for designers is to formulate strategies based on experiences of the attitudes and activities that may support serendipity (Makri et al., 2014).

In the first example from our case study, we learned that *allowing creative distractions* by combining an inquisitive mindset and creative thinking can lead to new methods and insights. By implementing input from users in the creative process through *co-creation*, we were exposed to knowledge, interpretations and emotions that were extremely different from our own. This instance of serendipity allowed us to gain new knowledge and see patterns that we could not have envisioned beforehand.

In the second example, the way people view themselves was found to be highly dependent on their situation. This highlights the need to consider how we, as observers, may affect the people we investigate in different situations and thus affect the collection and interpretation of data. To increase the likelihood of serendipitous outcomes, we suggest that design-driven field research could benefit from *switching methods*, such as switching from observation to eye tracking, and seeking out information-dense situations, such as work handovers.

In the third example, we found that a field study may involve a highly dynamic research environment in which many aspects affect the situation and there are few constant factors. As a result, the assumptions, insights and findings based on the collected data had to be developed or altered based on how the situation and research environment changed. In other words, it was useful and important to *accept ambiguity*.

Based on the examples above, we suggest four potential design strategies that might support serendipity in design-driven field research:

- **Allow creative distractions**: Ideas and design reflections may emerge suddenly while conducting planned field study activities. Taking time to spontaneously elaborate on design reflections through sketching or discussion of possible design solutions can allow the creative thinking process to take new and serendipitous directions.
- **Co-create with users:** Involve users and let their engagement affect the results of the creative process in context. By implementing input from users in the creative process, designers are exposed to logics, interpretations and relations that are different from their own, and the chance of seeing new combinations and patterns increases.
- **Switch or adjust the method**: If progress is unsatisfactory, the responses of the persons involved are not useful or the situation is better suited to another way of collecting data, switching one's method can be beneficial. Customized interactions with users in which researchers improvise and adjust their field research method based on the situation might generate more useful communication.
- **Accept ambiguity**: Be open to more than one interpretation. The discomfort of ambiguity drives one to understand and find solutions. Remaining open to a variety of interpretations of assumptions and insights can lead to richer or unexpected understandings or ideas.

Further research should investigate how these strategies can be planned for and implemented in field studies and how such implementation would affect serendipity in the field.

# 7. Conclusion

We presented a case study investigating serendipitous outcomes in two design-driven field studies that explored the potential of using AR on ship bridges. Elaborating on a framework for serendipity proposed by Rivoal and Salazar (2013) for the field of social anthropology, we investigated how a mixed-methods approach to design-driven field research may facilitate serendipity. We have described three examples of serendipitous outcomes from the field research and identified aspects that led to serendipity. Based on the examples, we suggested four strategies that might support serendipity in design-driven field research: *allow creative distractions*, *co-create with users*, *switch or adjust method*, and *accept ambiguity*.

Based on our case study, we suggest that a mixed-methods approach that accounts for serendipity can be valuable for design-driven field research, especially works intended to investigate new design problems, such as the use of AR on ship bridges. We suggest that designers could benefit from practical support when building their own approaches involving serendipity.

# References

Alterhaug, B. (2004). Improvisation on a triple theme: Creativity, jazz improvisation and communication. *Studia Musicologica Norvegica*, *30*(30), 97–118.

Alterhaug, B. (2010). Improvisation as phenomenon and tool for communication, interactive action and learning. In M. Santi (Ed.), *Improvisation: Between technique and spontaneity* (1st ed., pp. 103–134). Newcastle upon Tyne: Cambridge Scholars Publishing.

Baldauf, M., & Procee, S. (2014). *Augmented reality in ships bridge operation*. Paper presented at the International Symposium Information on Ships 2014, Hamburg, Germany. Retrieved November 14, 2018, from https://www.researchgate.net/publication/273057248_Augmented_Reality_in_Ships_Bridge_Operation

Benedict, K., Kirchhoff, M., Gluch, M., Fischer, S., Schaub, M., & Baldauf, M. (2016). Simulation-augmented methods for safe and efficient manoeuvres in harbour areas. *TransNav, International Journal on Marine Navigation and Safety of Sea Transportation, 10*(2), 193-201. Retrieved from http://www.transnav.eu/Article_SimulationAugmented_Methods_for_Benedict,38,641.html

Beyer, H., & Holtzblatt, K. (1997). *Contextual design: Defining customer-centered systems* (1st ed.). San Francisco, CA: Morgan Kaufmann.

Bonetti, F., Warnaby, G., & Quinn, L. (2018). Augmented reality and virtual reality in physical and online retailing: A review, synthesis and research agenda. In T. Jung & M. C. Tom Dieck (Eds.), *Augmented reality and virtual reality: Empowering human, place and business* (pp. 119–132). Cham, Switzerland: Springer International Publishing. Retrieved from https://doi.org/10.1007/978-3-319-64027-3_9

Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues*, *8*(2), 5–21. doi:10.2307/1511637

Carr, P. L. (2015). Serendipity in the stacks: Libraries, information architecture, and the problems of accidental discovery. *College & Research Libraries*, *76*(6), 831–841. doi:10.5860/crl.76.6.831

Colman, D. R. (2006). The three princes of Serendip: Notes on a mysterious phenomenon. *McGill Journal of Medicine: An International Forum for the Advancement of Medical Sciences by Students*, *9*(2), 161–163.

Crabtree, A., Rouncefield, M., & Tolmie, P. (2012). *Doing design ethnography* (2012 ed.). London & New York: Springer.

DeWalt, K. M., & DeWalt, B. R. (2011). *Participant observation: A guide for fieldworkers*. Lanham, MD: Rowman Altamira.

Erdelez, S. (2005). Information encountering. In K.E. Fisher, S. Erdelez, & L. McKechnie (Eds.), *Theories of information behaviour* (pp. 179–184). Medford, NJ: Information Today for ASIS&T.

Fine, G. A., & Deegan, J. G. (1996). Three principles of Serendip: Insight, chance, and discovery in qualitative research. *International Journal of Qualitative Studies in Education*, *9*(4), 434–447. doi:10.1080/0951839960090405

Frydenberg, S., Nordby, K., & Eikenes, J. O. H. (2018). Exploring designs of augmented reality systems for ship bridges in Arctic waters. In *RINA International Conference on Human Factors*. London, UK: The Royal Institution of Naval Architects.

Gernez, E., & Nordby, K. (in press). Implementing field research in ship design.

Halvorsen, B. (2016). *Design for serendipity: A research through design approach*. Retrieved from https://www.duo.uio.no/handle/10852/53765

Hanington, B., & Martin, B. (2012). *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Beverly, United States: Rockport Publishers.

Hareide, O.S., Mjelde, F.V., Glomsvoll, O. & Ostnes, R. (2017). Developing a High-Speed Craft Route Monitor Window. In: Schmorrow D., Fidopiastis C. (eds) *Augmented Cognition. Enhancing Cognition and Behavior in Complex Human Environments* (pp. 461-473). AC 2017. Lecture Notes in Computer Science, vol 10285. Cham, Switzerland: Springer International Publishing. Retrieved from https://doi.org/10.1007/978-3-319-58625-0_33

Hareide, O. S., & Ostnes, R. (2017). Maritime usability study by analysing eye tracking data. *The Journal of Navigation*, *70*(5), 927–943. doi:10.1017/S0373463317000182

Hughes, J., King, V., Rodden, T., & Andersen, H. H. K. (1994). Moving out from the control room: Ethnography in system design. In R. Furuta, & C. Neuwirth (Eds.), *Proceedings of the conference on computer supported cooperative work. Transcending boundaries* (pp. 429-439). New York, NY: Association for Computing Machinery. doi:10.1145/192844.193065

Kingdon, M. (2012). *The science of serendipity: How to unlock the promise of innovation* (1st ed.). West Sussex, UK: Wiley.

Lunenfelt, P. (2003). The design cluster. In B. Laurel (Ed.), *Design research: Methods and perspectives*. Cambridge, MA: MIT Press.

Lurås, S. (2016). Layered scenario mapping: A multidimensional mapping technique for collaborative design. *CoDesign*, *12*(3), 133–150. doi:10.1080/15710882.2015.1072221

Lurås, S., Lützhöft, M., & Sevaldson, B. (2015). *Meeting the complex and unfamiliar: Lessons from design in the offshore industry*. Retrieved September 21, 2017, from http://www.ijdesign.org/index.php/IJDesign/article/view/1845/697

Lurås, S., & Nordby, K. (2014). *Field studies informing ship's bridge design at the ocean industries concept lab.* Retrieved from https://brage.bibsys.no/xmlui/handle/11250/221073

Lurås, S., & Nordby, K. (2015). *Shaping designers' sea sense: A guide for design-driven field research at sea*. Retrieved from https://brage.bibsys.no/xmlui/handle/11250/2359373

Makri, S., & Blandford, A. (2012). Coming across information serendipitously - Part 1: A process model. *Journal of Documentation, 68*(5), 684–705. doi:10.1108/00220411211256030

Makri, S., Blandford, A., Woods, M., Sharples, S. & Maxwell, D. (2014). "Making my own luck": Serendipity strategies and how to support them in digital information environments. *Journal of the Association for Information Science and Technology, 65*(11), 2179–2194. doi:10.1002/asi.23200

Mauss, M. (Ed.). (2009). *The manual of ethnography* (1st ed.). New York: Berghahn Books.

McBirnie, A. (2008). Seeking serendipity: The paradox of control. *Aslib Proceedings: New Information Perspectives, 60*(6), 600–618.

McCay-Peet, L., & Toms, E. (2017). Researching serendipity in digital information environments. *Synthesis Lectures on Information Concepts, Retrieval, and Services, 9*, 1–91. doi:10.2200/S00790ED1V01Y201707ICR059

Merton, R. K. (2006). *The travels and adventures of serendipity: A study in sociological semantics and the sociology of science*. Princeton, NJ: Princeton University Press.

Norman, D. A., & Verganti, R. (2014). Incremental and radical innovation: Design research vs. technology and meaning change. *Design Issues*, *30*(1), 78–96. doi:10.1162/DESI_a_00250

Nordby, K., & Lurås, S. (2015). *Multimodal interaction for marine workplaces used as strategy to limit effect of situational impairment in demanding maritime operations*. In *RINA International Conference on Human Factors*. London, UK: The Royal Institution of Naval Architects.

Nunnally, B., & Farkas, D. (2016). *UX research: Practical techniques for designing better products*. Newton, Massachusetts, United States: O'Reilly Media, Inc.

Procee, S., Borst, C., van Paassen, M. M., & Mulder, M. (2017). Toward functional augmented reality in marine navigation: A cognitive work analysis. In *16th Conference on Computer and IT Applications in the Maritime Industries* (pp. 298-312). Hamburg, Germany: Technische Universität Hamburg-Harburg. Retrieved from http://resolver.tudelft.nl/uuid:67f92410-9e5a-452f-8fba-713f8d084cd2

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Science*, *4*(2), 155–169.

Rivoal, I., & Salazar, N. B. (2013). Contemporary ethnographic practice and the value of serendipity. *Social Anthropology*, *21*(2), 178–185. doi:10.1111/1469-8676.12026

Roberts, R. (1989). *Serendipity: Accidental discoveries in science*. New York: Wiley.

Rubin, J., Chisnell, D., & Spool, J. (2008). *Handbook of usability testing: How to plan, design, and conduct effective tests* (2nd ed.). Hoboken, New Jersey, United States: Wiley Publishing, Inc.

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign*, *4*(1), 5–18. doi:10.1080/15710880701875068

Schön, D. (1984). *The reflective practitioner: How professionals think in action*. New York: Basic Books.

SEDNA-project.eu. (2017). Retrieved November 28, 2017, from https://sedna-project.eu/

Serendipity. (2018). In *The American heritage dictionary of the English language* (4th ed.). Retrieved from https://ahdictionary.com/word/search.html?q=serendipity

Strauss, A., & Corbin, J. (1994). Grounded theory methodology: An overview. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (1st ed., pp. 273–284). Thousand Oaks: Sage Publications.

Sun, X., Sharples, S., & Makri, S. (2011). A user-centred mobile diary study approach to understanding serendipity in information research. *Information Research, 1*6(3) paper 492. Retrieved from http://discovery.ucl.ac.uk/id/eprint/1309397

Vallery-Radot, R. (1928). *The life of Pasteur* (R. L. Devonshire, Trans). New York City, United States: Garden City Publishing Company.

**Synne Frydenberg** has been a PhD fellow at the Oslo School of Architecture and Design (AHO) since 2017. She works as a design researcher for the SEDNA project. Her research interests include designing for situated interactions in complex professional settings.

**Jon Olav Eikenes** (PhD) is a designer and researcher at AHO. He works part-time as a design researcher for the SEDNA project and part-time at his own visualization company, Norviz AS.

**Kjetil Nordby** (PhD) is an associate professor at AHO. He is a research manager for Ocean Industries Concept Lab, and he has initiated and managed many design-driven research projects concerning the ocean industries.

**Acknowledgements:** The research presented in this paper was funded by the EU project SEDNA. This project receives funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 723526. Thanks to Nicholas Stevens for contributing ideas, observations and technical skills. Thanks to the SEDNA team for participating in the field studies, providing input and helping further the design processes. Thanks to Odd Sveinung Hareide and Robert Lynch for organising the field studies and to Hareide for an expert evaluation of one of our field study reports. Thanks to NTNU Ålesund for lending eye-tracking equipment to the researchers. Special thanks to the Norwegian Coastguard, the KV Svalbard and its crew, the Swedish Maritime Administration and the Icebreaker Atle and its crew.

# PUBLICATION 3

Nordby, K., Frydenberg, S., & Fauske, J. (2018). Demonstrating a maritime design system for realising consistent design of multi-vendor ship's bridges. In *Proceedings of the RINA international conference on human factors*. Royal Institution of Naval Architects.

Paper originally presented at RINA - International Conference on Human Factors, 26 – 27 September 2018, London.

# DEMONSTRATING A MARITIME DESIGN SYSTEM FOR REALISING CONSISTENT DESIGN OF MULTI-VENDOR SHIP'S BRIDGES

**K Nordby, S Frydenberg** and **J Fauske,** The Oslo School of Architecture and Design, Norway

## SUMMARY

Maritime workplaces in digitally integrated multivendor ship's bridges often offer inconsistent user interfaces and suboptimal workflows for navigators. We propose that design consistency in such bridges can be achieved by applying methods and technologies from the web and mobile industries. We present ongoing design work directed towards defining a maritime design system enabling design consistency across multi-vendor ship's bridge systems. The system has been developed through an experimental process involving analysis of 10 user interfaces from existing ship's bridges to understand their functional structure. We further apply design strategies from the web industries, such as responsive design, style theming and standard user interface components. We present a design proposal and discuss the results in terms of consistency and the implications for industry of having a maritime design system. We argue that there are compelling advantages for the maritime industry in systematically transferring methods, processes and tools from the web industry.

## 1. INTRODUCTION

In a study investigating the impact of technology on safety for ship operators, Mišković, Bielić and Čulin found that 37% of the respondents had operated three or more types of integrated bridge systems (IBS) [1]. Further, they stated that 27% of the operators reported having been confused by the information provided in the systems, linking the effect to the operators encountering too many different types of equipment. Adding to these challenges is the fact that many ship's bridges do not have fully integrated IBS but are equipped with systems assembled of equipment delivered by multiple vendors. In field visits, we have observed such multivendor ship's bridge systems (MBS) consisting of up to 35 different types of equipment. These separate equipment units would be physically installed in large work consoles, leading to cluttered workplaces with suboptimal organisation of the space around the navigators [2].


Figure 1: SEAQ bridge delivered by Vard Group AS. (Photo: Vard Group AS)

In order to deliver improved workplaces, a number of MBS integrators have started to integrate equipment digitally in their workplaces. Figure 1 shows an example of one such bridge, delivered by Vard Group AS, that allow users to access equipment through touch screens. In these systems, the separate equipment units are mediated as applications with digital user interfaces that share screens and interaction devices. By *user interfaces*, we mean the access points where the user can interact with the system. These MBS are similar to IBS, but because separate companies design many of the applications, there is a great deal of variation in user interface design within each MBS.

*Design consistency* across applications has long been fostered in the web industry through various approaches. Here, we explore how a selection of these approaches may be applied to maritime user interfaces in order to achieve design consistency. We examine this through an experimental process in which we deconstruct the user interfaces of current ship's bridge equipment and redesign them using consistent design methods drawn from the web industry.

Our work is part of an industry-driven research project called Openbridge [3] that seeks to harmonize implementation and user experiences of user interfaces in MBS. The project consists of 20 industry, research and government partners and is led by Ocean Industries Concept Lab from The Oslo School of Architecture and Design.

### 1.1 DESIGN CONSISTENCY

Design consistency is one of many factors that are important in designing user interfaces. Nielsen has suggested that consistency supports the user's ability to transfer skills from one system to another and may lead to ease of learning, ease of use, higher throughput and reduced errors [4]. Design consistency can encompass many dimensions of user interface design [4]. For instance, it can relate to aspects of the graphic design of the user interface, such as spatial organisation of components, colours, symbols and typography, and to aspects of interaction design, such as structure of content, user interface patterns, terms and interaction mechanisms. Consistency can also be applied within a single application (e.g. Electronic chart display and information system (ECDIS)), across multiple applications working within a single system (e.g. an IBS) or across multiple systems each with multiple applications (e.g. across several IBS). Consistency cannot cross all aspects of an application, and consistency can in some cases result in suboptimal user interfaces [5]. Design for consistency must therefore consider users' activity.

The lack of design consistency in the maritime industry has been well known for many years, and International Maritime Organization (IMO) initiatives such as S-mode are trying to move the industry towards improved consistency across maritime user interfaces [6]. S-mode seeks to introduce a switch that would enable a standard user interface for navigation systems. Despite such efforts, current regulations and laws have not led to clear premises for consistent design across the many vendors delivering equipment for MBS. A consistent MBS requires consistency across a number of applications, and this is challenging from an organisational perspective since multiple vendors needs to agree on design guidelines specific enough to achieve design consistency. This is also problematic from a commercial perspective because user interfaces are part of both system integrators' and equipment vendors' unique value offerings.

### 1.2 CONSISTENCY IN WEB INDUSTRIES

In web and mobile-oriented industries (web industries), there is a long tradition of addressing design consistency through the development of design guidelines [7-9]. Developers of operating systems (such as Android, Windows and iOS) have tackled the problem by producing and distributing comprehensive design guidelines connected to software development resources that make it convenient for application developers to follow their design philosophy [7-10]. For operating system vendors, this move promotes consistent design that improves the usability of the applications built for their platforms. For system developers and designers, these guidelines contribute to improving their design delivery and ensure that the applications are consistent with the general platform on which they operate. This results in applications that are easier to learn at launch since users are already familiar with central aspects of their user interface based on previous experience with other applications.

Current generations of web-based design guidelines often take the form of a *design system*. By design system, we refer to a modular user interface methodology built on web technology that merges traditional design guidelines with development tools. A design system should be an adaptive system that supports a portfolio of applications and is in continuous development to respond to new needs [11]. The thinking behind design systems is not new [4]; however, it has gained traction in recent years as a way of reducing development costs and improving user experience (UX) for companies with large portfolios of applications. UX, which is often used as a qualitative measurement of success [12], refers to a user's dynamic, context-dependent and subjective experience of the system [13].

Although building a design system requires extensive and comprehensive work, it will ultimately save both time and money as the design system is applied to increasingly more applications and services. This is because a design system includes reusable components that simplify implementation and design processes. Because consistency and cost are important challenges in the maritime industry, we suggest that applying the thinking behind design systems might be beneficial in this domain.

## 2. DESIGN CONSISTENCY IN MARITIME USER INTERFACES

In reviewing current design regulation and guidelines in the maritime sector, we found no information about how to realise consistent design across different vendors [14]. Although maritime regulations and guidelines offer important support of screen based user interface design, they do not provide user interface guidelines with the specificity that is necessary to achieve design consistency. In addition, we found no support for achieving more cost-effective design of new user interfaces.

We argue that there is a gap between state-of-the-art web-based design support and design support specific to the maritime industry. To bridge the gap, we argue that it would be beneficial for the maritime industry to develop a design system based on approaches from the web industry to help achieve design consistency across maritime applications.

To do so, it is important to distinguish between an integration platform and applications. An integration platform includes the workstation and the software that manages how applications are mediated in the workplace. Applications are software programs (such as Dynamic positioning system (DP), ECDIS and wiper control systems) installed within the integration platform. A full maritime design system would cover both areas. However, this article addresses only consistency among applications. We will explore consistency across multiple complete MBS in forthcoming articles.

In order to develop a design system proposal, we have compared the user interfaces of 10 maritime applications:

- Compass system

- Echo sounder
- Deck light system
- 2 conning displays
- Electronic charts
- Alert system
- Automation system
- Application launcher
- Propulsion indication interface

The selected applications represent a wide range of digital user interface types found in ship's bridges. We have evaluated design consistency across these 10 interfaces and identified the components used to build them. Our analysis is divided into three categories: user interface components, user interface layout and user interface style. These represent common categories for organising web-centric user interface guidelines.

### 2.1 USER INTERFACE COMPONENTS

User interfaces are constructed using a set of components for input control, such as buttons and toggles, navigation, such as search field and sliders, and information, such as icons and notifications. In order to achieve consistency, the appearance and use of such components should be similar across all applications.

None of the interfaces we analysed used user interface components from a shared library; all opted for individual design. This resulted in much variation even in very simple interaction components, such as buttons. The variations extend to graphical icons and maritime user interface components, such as representations of thrusters. We found no functional reason for the variations in user interface component design.

### 2.2 USER INTERFACE LAYOUT

We refer to the overall structure of a user interface as the user interface layout. This includes the division of screen space into functional areas as well as rules for the position of important function categories, such as function and navigation menus.

We found significant variation in the user interface layouts of the 10 applications we analysed. The variations were related both to the separation of functions and to the positioning of function categories. Some of this variation can be attributed to many applications targeting different modes of operation and having different types and quantities of information and functionality. For instance, the user interface for the echo sounder represents a much narrower scope of information than that of the conning application. However, even in such cases, we do not see any reasons for the difference in layout with regard to the positioning of navigation menus and alert components, for example.

Nine of the applications were custom-made for a fixed screen resolution and could not be scaled to other screen formats, distances and resolutions without redesign. In some of the user interfaces, this was already a problem, as some of the applications were positioned farther away from the user than their interfaces had been designed for. We argue that a layout structure allowing adaptive scaling would be beneficial in many of the user interfaces.

### 2.3 USER INTERFACE STYLE

User interface style addresses visual formatting, such as typography, colour, spacing, iconography and the appearance of shapes and lines. Visual formatting is important in maritime applications because it is connected to readability and the design of day and night palettes. In addition, it conveys the visual identity of companies that make equipment and bridge systems.

Overall, we found no consistency across components, layout or style in the 10 applications we examined. We consider this lack of consistency problematic and contend that it most likely would lead to usability problems if the applications were installed in the same MBS.

## 3. TOWARDS A MARITIME DESIGN SYSTEM

We propose to develop a design system for the maritime domain able to support consistent design and efficient implementation of user interfaces for maritime applications, especially targeting MBS. Our maritime design system will include design guidelines aligned with maritime regulations, maritime-specific content, online support material and online development libraries supporting user interface implementation.

This article reports on processes aimed at the development of such a maritime design system, focusing on our collaboration with industry partners to develop an early concept for design guidelines to support application design for MBS. Our current proposal is not a full design system but a substantial step on the way towards this goal. The main purpose of our proposal is to demonstrate whether technologies and methods from web industries can be applied to maritime applications to realise consistency.

The proposal has been developed using an iterative design process where we redesigned existing user interfaces using concepts from web-based design guidelines. We especially draw on Google material design [6] due to its comprehensive connected support material and its familiarity as one of the best-known design systems. By iteratively designing multiple applications in parallel, we are able to identify common user interface elements and synchronise the design across applications. This process is repeated in a continuous loop as we try to achieve meaningful consistency in the components, layout and style of the user interface.

We have reviewed our design proposal through two industry workshops with partner companies and through expert evaluation by designers and human factor specialists working in the maritime domain.

The designs have been developed using common tools for user interface design, such as paper sketches, graphic design software and web development tools. We have developed a global style guide in parallel to the design of individual applications. In addition, we have implemented a few of the user interfaces as responsive HTML demonstrators to test scaling in practice. These have been installed in an MBS made by one of the project partners for compatibility testing. The current proposal is an early iteration of a design system and is not ready for industrial implementation. We consider it a framework for further design of a functional maritime design system.

## 3.1 DESIGN CONCEPT

Our design concept simplifies current application designs by limiting variations in visual style, layout and components. In addition, we strive to remove redundant information in the various user interfaces.

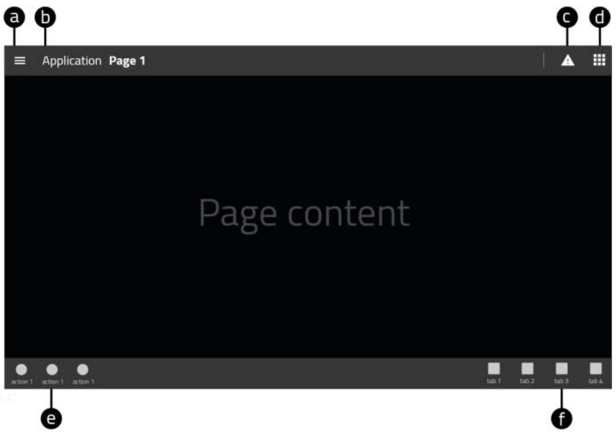



Figure 2: Main user interface window: a. hamburger menu, b. main title, c. alarm component, d. global navigation menu, e. action buttons and f. tab menu.

The proposed design system calls for application interfaces based on a simple frame with a top bar and a bottom bar (Figure 2). The bottom bar is optional if this space is needed for user interface functionality. A hamburger menu in the top left corner (Figure 2a) provides access to navigation within the application. The lower left corner has space for action buttons targeting the content area of the application (Figure 2e). The lower right corner has space for an optional tab menu providing access to application functions (Figure 3d). The top right corner has a fixed area for the alert system (Figure 2c). In addition, there is a button that offers access to a global navigation menu to swiftly switch applications and to change the palette and dimming options (Figure 2d). Central icons in the navigation menu can be placed to the right of the navigation menu button if necessary. Within the hamburger menu, the top area is reserved for navigation within the current application (Figure 3a) and settings (Figure 3b). The lower area allows access to company-specific information and the help system (Figure 3c). We have standardised the placement of important generic functions, such as dimming (Figure 2d), palette control (Figure 2d), help (Figure 3c), company messages (Figure 3c) and alerts (Figure 2c).

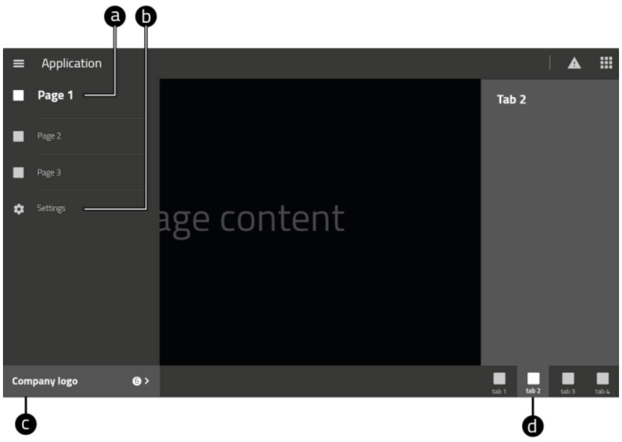



Figure 3: Main user interface window with hamburger menu revealed: a. settings button, b. navigation button and c. company-specific flyout.

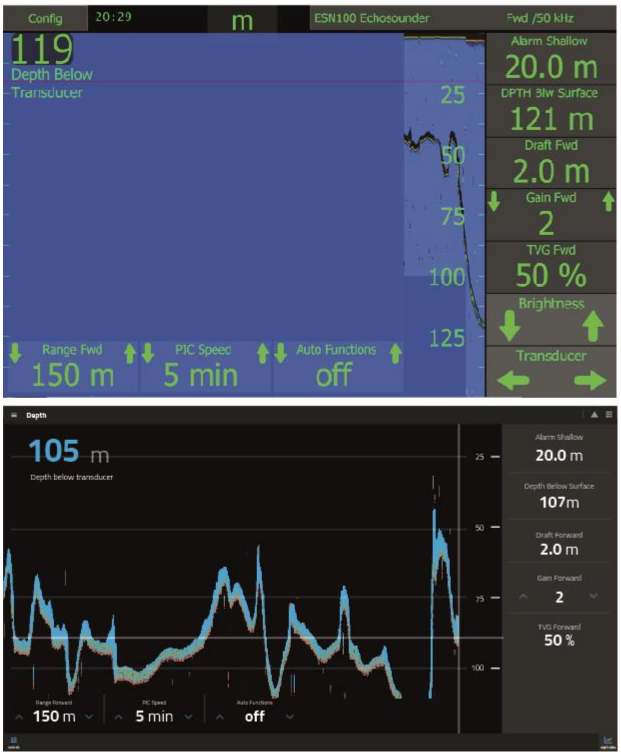



Figure 4: Comparison of old user interface (left) and new user interface (right).

Figure 4 shows an example of an actual application design and the same application converted to the new template. The new template adds new functionality, such as free scaling and optional hiding of menus. The design also allows comprehensive changes in visual style. The palette in figure 4 is drawn from some of the partner companies' application implementations. We are in the process of designing a new palette that conforms to maritime regulations.

Our design proposal makes use of several approaches found in web-based user interface design: theming, responsive design, common user interface component design and a user interface component library. What follows is a description of each of these strategies and a walkthrough of how we have implemented it in our design.

3.1 (a) User Interface Components

Although we found significant variation in the *design* of user interface components in our analysis of current systems, we also saw that the number of component *types* was quite small, dominated by buttons, toggle buttons and menus. Our design proposal makes use of the component types we found in our analysis and proposes new common components inspired primarily by material design (Figure 5).

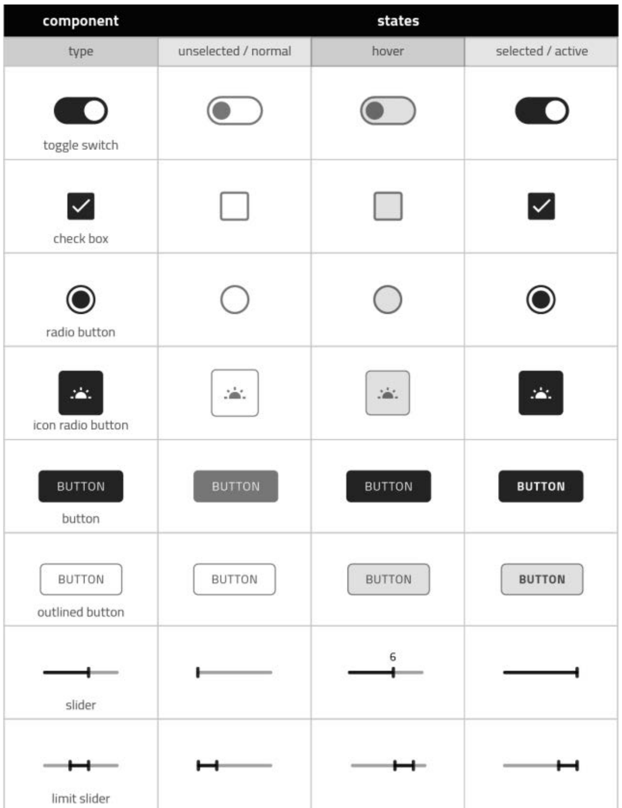



Figure 5: Generic user interface component library.

We opted to scale the buttons for touch interaction for two reasons. First, touch interaction is common in modern user interfaces for ship's bridges. Second, implications of fatigue and a moving environment may potentially affect a person's ability to identify and trigger a button, so we assume that larger hit areas are a benefit in maritime systems in general. This choice needs further evaluation in formal user tests. Future iterations of the concept may differentiate between components for touch interaction and components for screens operated through indirect interaction, such as by mouse.

In addition to user interface components borrowed from web industries, we have defined an additional category of maritime-specific user interface components. There are a number of interaction components that represent specific types of data, such as visualisations of heading and thrusters. We have identified these as *maritime user interface components* connected to specific maritime content. Also within this group are components that mediate specific generic functions in the user interface, such as the alarm component and the dimming component.

3.1 (b) Theming

It is common in web development to separate definitions of application styles from other code and to use cascading style sheets (CSS) and similar technologies to format the visual style of an application. This method makes it possible to change user interface attributes, such as spacing, fonts, colours and geometry, for any number of user interfaces by simply editing a global CSS file. Figure 6 show an example of a toggle button formatted by two palettes. Theming across an MBS would enable uniform day and night palettes and a custom style guide to accommodate individual users and would also allow adaptation of the visual style of any application to an integrator's design scheme. This approach would make it possible for an equipment manufacturer to deliver a single application that could automatically be adapted to different style guides on different MBS.

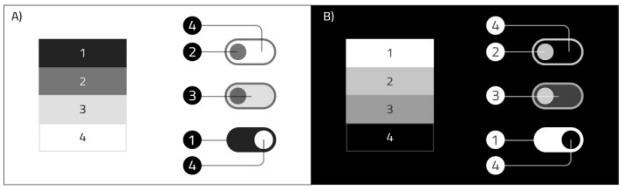



Figure 6: Colour palette connected to a toggle button user interface component. a. Light palette, b. Dark palette.

We have based our approach to theming on our partner companies' needs to adapt the look and feel of the design guidelines. To facilitate this goal, we have integrated fonts, colours, line thickness and border shape into the CSS specification. The system can be used to format a single application or all applications within the MBS. This allows us to achieve complete aesthetic conformity across workplaces and opens up new possibilities, such as allowing ship owners to implement their own style guide on an MBS.


Figure 7: Comparison of three visual themes.

The lower two themes in Figure 7 are based on existing design guides used by integrators in the project group. The two designs demonstrate that we can replicate some of the visual identity of existing systems through CSS while maintaining the layout and component design of our design system.

The theming functionality of the design system is based on a taxonomy of the elements that make up the visual representation of the applications. This include lists of allowed text formatting, line types, geometry types, icon formatting and colour palettes. To ensure that all graphics can be formatted through CSS, we do not allow use of images (raster graphics) as part of user interfaces. Instead, all graphics are generated as vectors, which support colour changes using CSS while having the advantage of supporting free scaling without pixilation.

Maritime theming will differ somewhat from current web-based templates. First, the design must facilitate multiple palettes related to operational conditions, such as night, dusk and dawn palettes. Second, maritime requirements and user needs warrant the connection of some colours to specific functionality, such as alerts. Third, the system must facilitate text scaling based on viewing distance in addition to screen size.

### 3.1 (c) Responsive Layout

As mobile phones took over as the primary platform for consumption of web services, the web industries recognized the need for streamlined web page design that could scale across multiple screen sizes. Responsive design or responsive layout solved this problem by establishing rules to define how a web page or application would rearrange its content according to how it was accessed [15].

Many of the participants in our consortium have reported the difficulty of supporting multiple screen sizes and types. Responsive design has the potential to solve these problems as well as allow user interfaces to be reused on new platforms, such as phones. Responsive design is commonly used for scaling content-rich web pages for different platforms. However, even if the content is different, we may use many of the patterns of responsive design for maritime applications.


Figure 8: Responsive scaling of size and distance.

Our concept uses a simple scaling scheme in which text, icons and other user interface components maintain a consistent scale when the user interface is scaled for a larger or smaller screen size. In addition, we support independent scaling of text and interaction components based on the user's distance from the screen (Figure 8). This is particularly important on ships where screen distance may vary tremendously.

In order to keep interaction components from overlapping at small screen sizes, we have introduced two breakpoints. A breakpoint defines a certain size threshold where the user interface is rearranged to better facilitate a new range of display area sizes. In our design, the thresholds rearrange the menu structure in the interface. The first collapses the right action menu, while the second removes all remaining menus and effectively transforms the application to a widget-type app.

Our trials show that we can replicate most of our applications with responsive design to allow them to scale freely from very small form factors to large screens. Adjusting to smaller form factors requires the hiding of parts of the interface, and many of the applications will need a defined minimum screen area to ensure that they can safely show essential content for maritime operations.

There are multiple reasons for adopting responsive design in maritime applications. The modern ship's bridge already has multiple screen types and sizes. Moving forward, we expect there will be additional formats made available, including higher screen resolutions, larger screens and portable formats. Further, as systems are accessible over a network, it is likely that users will access maritime applications in many places. Finally, these applications are installed on multiple ships, and as available screen formats increase, it is likely that the same application will be shown on different screen formats on different ships.

## 4. DISCUSSION

The presented concept is a work in progress and not a finished design system. However, based on our experience so far, we argue that the work shows that it is possible to create a maritime design system based on web technology that can achieve consistent user interfaces across a wide variety of applications. The implementation of a maritime design system may realise the goal of design consistency across applications, leading to improved usability when compared with the current MBS implementations we have observed.

Although the main contribution of the concept is to offer a pathway for *inter-MBS consistency* (consistency across several systems) and *intra-MBS consistency* (consistency within a single multivendor ship's bridge system), we believe the system can also improve individual applications. Such a design system would go much further than current maritime regulations in specifying how to design applications for maritime use. This would be especially beneficial for smaller companies with limited resources for user interface design. Many of our partners report that clearer guidelines would improve the design quality of their current offerings as well as reduce design and implementation costs.

The applications we have designed are self-contained individual applications that will sometimes exist within a larger integration system, much like apps on smartphones. This represents a challenge for the designer who may not know how the main integration system organizes menus or switches between applications. Our design system handles this by providing for the consistent placement of global navigation in each application. However, if an integration system design conflicted with our approach, a change would need to be made either to the integration system or to our design system. Examples of such conflicts could be a global top bar in the integration system that obscures the application top bar or flyout menus for navigation in the integration system that overlap application menus. To avoid such conflicts, we argue that a successful maritime design system must include specifications for how integration systems should facilitate the integration of applications. We will extend our design work to encompass requirements for integration systems as we further develop the concept.

Many of our partner companies use interface design to differentiate their products. This is a barrier to introducing a uniform maritime design system. Many of the industry actors we collaborate with are worried that a strong design system would reduce their ability to stand out in the market. We have made efforts to relieve such concerns by opening up the possibility of differentiating user interfaces through styling (facilitated by CSS) while maintaining consistency across MBS through the layout and components. This would make it possible for individual applications or entire bridges to be presented in company-specific styles. However, our design system will still strongly regulate individual actors' ability to freely design large portions of their user interface.

We have found no equivalent system openly available for maritime application development. The only systems we have found are companies' internal design systems that cannot be used by outside companies. There are also significant differences between our design and the current dominant web-based design systems. First, the maritime design system must be very rigid in accordance with our strong emphasis on consistency. Second, use of colours must adapt to maritime needs, providing for day and night palettes and the restriction of specific colours to particular functions. Third, a range of maritime-specific user interface components is required. Fourth, the system must be able to support multiscreen environments; and fifth, the system needs to integrate maritime regulations that affect user interface design.

Because of differences between maritime needs and the objectives of current web-oriented design systems, we cannot directly apply these existing systems to the maritime domain. Instead, we need to adapt these systems to maritime-specific needs. However, by using web-based systems as a basis for new design, we may build on the tremendous progress already made in a very large global industry in order to improve maritime systems.

Our current work focuses on graphical user interfaces. However, maritime user interfaces exist in in shifting and demanding conditions that affect users' ability to make use of equipment [16]. Because of this, we argue that maritime design systems will need to include multimodal and in particular tangible user interfaces [2,16]. We will explore such options in future research.

## 5. CONCLUSION

We have presented the first stage of a design system for maritime user interface design. Our work shows how web-based design methods and tools may be applied to the maritime industry in order to achieve consistent design in MBS. Our concept provides an example of how we can achieve consistency across layout, user interface components and style. The approach opens up the opportunity for multiple constellations of consistency, where for instance application layouts and use of components are consistent across any MBS using the same design system while style is managed within the individual MBS. Such a maritime design system can be an important contribution to improved user interfaces and UX in MBS.

## 6. ACKNOWLEDGEMENTS

Thank you to the Openbridge consortium for contributing to this article. The project is funded by the Openbridge Consortium and the Norwegian Research Council.

## 7. REFERENCES

1. MIŠKOVIĆ, D., T. BIELIĆ, and J. ČULIN, 'Impact of Technology on Safety as Viewed by Ship Operators', *Transactions on Maritime Science*, 2018, **7**(01): pp. 51–58.

2. NORDBY, K. and A.D. MORRISON, 'Designing Calm Technology and Peripheral Interaction for Offshore Service Vessels', *Personal and Ubiquitous Computing,* 2016, 20(4): pp. 601–613.

3. OPENBRIDGE, 'Openbridge Project Webpage', 2018 [cited 2018 April]; available from: www.openbridge.no.

4. NIELSEN, J., 'Coordinating User Interfaces for Consistency', 2014: Elsevier.

5. GRUDIN, J., 'The Case against User Interface Consistency', *Communications of the ACM,* 1989, **32**(10): pp. 1164–1173.

6. HAGEN, J.E., 'Implementing e-Navigation', 2017: Artech House.

7. APPLE, 'iOS Design Themes' [cited 2018 April]; available from: https://developer.apple.com/design/human-interface-guidelines/ios/overview/themes/

8. GOOGLE, 'Material Design' [cited 2018 April]; available from: https://material.io/guidelines/

9. MICROSOFT, 'Design Basics for UWP Apps', [cited 2018 April]; available from: https://docs.microsoft.com/en-us/windows/uwp/design/basics/

10. APPLE, 'macOS Design Themes', [cited 2018 April]; available from: https://developer.apple.com/design/human-interface-guidelines/macos/overview/themes/

11. CURTIS, N., 'Modular Web Design: Creating Reusable Components for User Experience Design and Documentation', 2010: New Riders.

12. BEVAN, N. 'Classifying and Selecting UX and Usability Measures', *International Workshop on Meaningful Measures: Valid Useful User Experience Measurement*, 2008.

13. LAW, E.L.-C., et al., 'Understanding, Scoping and Defining User Experience: A Survey Approach', *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems,* 2009: ACM.

14. MALLAM, S.C. and K. NORDBY, 'Assessment of Current Maritime Bridge Design Regulations and Guidance', 2018, The Oslo School of Architecture and Design: Oslo, Norway.

15. GARDNER, B.S., 'Responsive Web Design: Enriching the User Experience', *Sigma Journal: Inside the Digital Ecosystem,* 2011, 11(1): pp. 13–19.

16. NORDBY, K. and S. LURÅS, 'Multimodal Interaction for Marine Workplaces Used as Strategy to Limit Effect of Situational Impairment in Demanding Maritime Operations', *International Conference on Marine Design*, 2015: London.

## 8. AUTHORS BIOGRAPHY

**Kjetil Nordby** holds the current position of associate professor at The Oslo School of Architecture and Design. He is research manager for Ocean Industries Concept Lab and project leader of the Openbridge project. His previous experience includes interaction design, industrial design, design management and research management within the ocean industries.

**Synne Frydenberg** has been a PhD fellow since 2017 at The Oslo School of Architecture and Design. She also works part time as a design researcher within the SEDNA project. Her research interests lie in how to design for situated interaction in complex professional settings, such as a ship's bridge. Before starting her PhD, she worked six years as an interaction designer in the Norwegian design consultancy Making Waves and in the Norwegian publishing house Gyldendal's digital department.

**Jon Fauske** holds the current position of research assistant at The Oslo School of Architecture and Design. He is responsible for user interface design of the Openbridge design system. His previous experience includes industrial and interaction design.

# PUBLICATION 5

Frydenberg, S., Aylward, K., Nordby, K., & Eikenes, J. O. H. (2021). Development of an augmented reality concept for icebreaker assistance and convoy operations. Journal of Marine Science and Engineering, 9(9), Article 996. https://dx.doi.org/10.3390/jmse9090996

Working paper - Submitted to COMPIT 2020 Conference

# Augmenting OpenBridge: An open user interface architecture for augmented reality applications on ship bridges.

Kjetil Nordby, Etienne Gernez, Synne Frydenberg and Jon Olav Eikenes

*Ocean Industries Concept Lab, The Oslo School of Architecture and Design, Norway*

## Abstract

Augmented reality (AR) technologies support navigators by overlaying the perceived world with virtual information collected from the ship bridge systems. However, the variety of operational scenarios, types of ships and bridge equipment from different vendors requires an integration system that enables multiple maritime applications to employ AR as a shared platform. We address the lack of such a system by proposing a user interface (UI) architecture that describes how AR can function as an open, shared platform across different bridge systems by supporting the integration of generic maritime applications in AR.

## Introduction

Head-mounted augmented reality (AR) technologies can augment the perceived world by overlaying it with digital content. Recent developments in AR technologies, particularly the introduction of Microsoft HoloLens (Microsoft, 2020), have increased the number of potential applications in the market. Industrial sectors, such as aerospace, automotive and manufacturing, have already shown extensive use of the technologies (Capgemini Research Institute, 2018). In our user-centred exploration of AR technologies and applications, we discovered a variety of potential use scenarios for AR in the maritime domain (Frydenberg et al., 2018a, 2018b). In addition, we reviewed some initial experimental uses of AR (Nordby et al., 2020), including support for ship bridge crew during navigation and operation (Erlandsson and Jansson, 2004; Hareide and Porathe, 2019; Procee and Baldauf, 2014), support for shipyard floor workers (Friedewald et al., 2015; Matsuo, 2016), and support for remote inspection and maintenance of ship systems (Helle et al., 2014; Lee et al., 2010).

AR technologies can support navigators in their work by presenting data from the ship bridge systems to augment the navigator's real world. The navigator may interact with and monitor the bridge systems while simultaneously maintaining focus on the primary visual field outside the ship. AR may improve operator performance and situation awareness (SA) by supporting navigation focus, reducing information overload and linking real and digital information (Rowen et al., 2019).

However, to realise these benefits, AR technologies must to be adapted to maritime users' needs (Nordby et al., 2020) and their environmental and technological contexts (Nordby and Morrison, 2016). There is a range of issues that can increase the threshold for safely applying AR technology in the maritime sector. For instance, the ship as a reference point is constantly moving; lighting conditions may vary from pitch black to extremely bright light; temperatures may differ within a wide range; users may suffer from fatigue or motion sickness; and users often move around the bridge while working (Frydenberg et al., 2018a).

In this article we focus upon three types of challenges that must be overcome in order to realise the benefits of AR for ship bridge users. First, a ship bridge is assembled by a multitude of systems that are often delivered by multiple actors with no common user interface (UI) design guidelines across these systems (Nordby et al., 2019a). As a result of poor integration between the systems, navigators often exert high levels of effort and awareness to integrate the translations, overlaps and gaps between the various UIs of the ship bridge systems (Lützhöft and Nyce, 2008). In this context AR applications need to be able to function as a common UI platform that can mediate between any maritime application on the ship bridge. However, there is no previous research on how AR technologies can be designed and implemented as a part of a consistent ensemble of ship bridge systems (Nordby et al., 2020).

Second, AR applications may use the entire world as a canvas to display digital information, and therefore a definition of how multiple systems may share the world is needed. For example, there is a need for structuring visualisation formats and their placement and managing how multiple information elements may share the world. Currently, no definition exists for how single or multiple AR applications may safely be rendered over the world (Nordby et al., 2020).

Third, the ship environment and the work situation of the bridge users constantly change during operations. As a result, a system is needed for how bridge users can adapt the AR interfaces to changing needs. Currently, we have found no practical or theoretical examples of AR used in the maritime domain that show how AR applications adapt to changing work conditions and tasks (Nordby et al., 2020).

Overall, there is a lack of frameworks that describe how multiple maritime systems can be designed to enable efficient exploitation of AR on a ship bridge. We address this problem in this article by proposing a system designed to enable multivendor ship bridge systems to share AR as a generic platform for safe use in ship bridges. Our design proposals are iteratively built towards assembling what is referred to as a “system architecture” in computer science and software engineering. Allen (1997, p. iii) explains that the architecture of a system “provides a model of the system that suppresses implementation in detail, allowing the architect to concentrate on the analyses and decisions that are most crucial to structuring the system to satisfy its requirements.” In order to support the work of ship bridge users, our work focuses on the development of a UI architecture of AR applications that provides bridge users with digital information overlaying the real world in a safe and efficient way. The current version of the UI architecture is built upon the OpenBridge Design System, which includes a UI architecture for maritime workplaces that emphasises screen-based, graphical UIs (Nordby et al., 2019b, 2018).

A UI architecture for AR needs two main components: AR applications and an integration system. AR applications are software programmes that make use of the integration system to access information-augmenting functionalities in a way tailored to the user’s needs and their work context. Current AR systems like the Windows Mixed Reality framework (Microsoft, 2020) have a similar structure, in which users may open multiple applications simultaneously and place them in a shared space. This approach is inspired by, and derived from, the mobile and internet technologies, in which “apps” are built to behave harmoniously across all the different platforms that use a common operating system, such as Android or iOS. However, our experience is that the Windows Mixed Reality framework is not well adapted to maritime needs and is not tailored to support situational awareness in maritime operations.

This work is part of the SEDNA EU research project and some of the concepts we describe here have been discussed in a previous project report (Nordby, 2019). SEDNA is developing an innovative and integrated risk-based approach for safe Arctic navigation, ship design and operation. Our approach at the architectural level enables us to focus on specific Arctic navigation use, while also proposing solutions that may apply to other cases. In the next sections, we first present our research approach and methods, then introduce the different components of the UI architecture and give examples of AR applications built for this architecture.

# Research approach

We employed user-centred design (UCD), an approach that involves users throughout the development process, to make sure that the solutions we created are anchored in the identified needs of actual users (Giacomin, 2014). The research activities took place in our lab facilities and during design-driven field research (Lurås and Nordby, 2014) onboard an ice breaker vessel and an ice class coast guard vessel engaged in operations and expeditions.

We carried out the research of developing the UI architecture with the explorative approach illustrated in Figure 1. It describes a parallel process containing a practical level and an abstract level that runs in iterations.

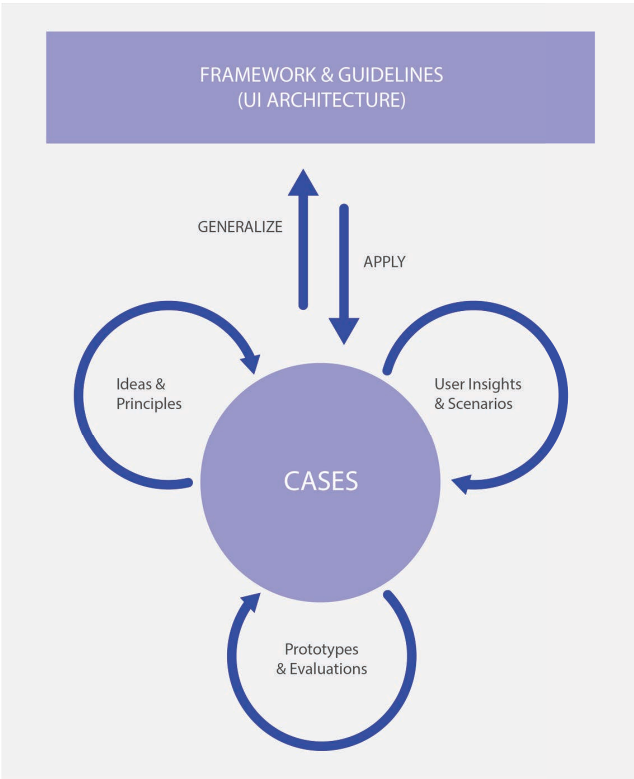



*Figure 1. UI architecture process model describing the iterative development of frameworks and guidelines based on case studies.*

Since our research process has continuous feedback loops, we present the method in parts rather than in a linear fashion.

## Design cases

At the practical level ("Cases" circle in Figure 1), we have a case we need to solve. An example of a case might be to develop a route planning tool for ice going vessels in a convoy. The process of solving a case involves three kinds of activities: 1) creating ideas and principles, 2) collecting user insights and constructing scenarios and 3) developing and evaluating prototypes.

**Creating ideas and principles:** We developed a wide collection of design ideas for potential use in bridge system applications, information display and the definition of AR zones. The ideas are provided as sketches with description. Based on these ideas, we worked further with design principles, schemas and diagrams to describe their use.

**Collecting user insights and constructing scenarios:** Gathering user insights is a continuous process embedded in all forms of activities where users are involved. During our design-driven field research at sea, we have employed an explorative and opportunistic approach by using methods such as participatory observation (DeWalt and DeWalt, 2011), semi-structured interviews (Kvale, 1996), eye-tracking (Hareide and Ostnes, 2017) and co-design (Sanders and Stappers, 2008). The mixed-methods approach for investigating the premises of designing AR systems for navigators, resulted in a broad set of both targeted and serendipitous data in form of images, videos, notes, recordings and test protocols (Frydenberg, Eikenes and Nordby, 2019). The data have been analysed through expert evaluations during collaborative data analysis workshops (Millen, 2000). Additionally, the data has formed basis for further idea creation and prototype development. Finally, the data helped to define operational scenarios that we used as a basis for developing ideas and prototypes for each case. We used layered scenario mapping to work with the scenarios (Lurås, 2016).

**Developing prototypes and evaluations:** Techniques for prototyping AR applications range from paper sketches to virtual reality (VR) environments in which AR UIs are embedded. VR enables a fast and cost-effective prototyping process with high levels of realism. We built a prototyping platform that combines a cloud-based simulator with a VR environment that uses the Unity game engine (Unity, 2020). The VR scene has a realistic ocean environment that can handle several ships at the same time, and allows the daytime, light and weather conditions to be modified. Realistic simulation data (for example, ship speed, heading, engine power load, etc.) can be fed into all the UIs present in the VR scene, including simulated AR UIs. In addition, the simulator data can be used in “real” AR UIs running on an AR headset (a Microsoft HoloLens in the current version of the platform). We tested the prototypes both in the lab and with expert users in the field to evaluate the usability of the AR concepts. In addition to the expert evaluations, data were collected through videos captured from the VR environment using the virtual camera of the VR headset or a secondary virtual camera.

## Framework and guidelines

At the abstract level (rectangle in Figure 1), we aim to develop frameworks and guidelines based on our previous cases that can ultimately support solving new cases. The process of generalisation is performed first by analysing the case in order to understand its parts, relationships and premises; second, we identify all the common characteristics we believe are shared among other cases; third, we formulate these characteristics as general concepts that we need to refine by acquiring more knowledge about them, categorising and organising them, putting them into a hierarchy and understanding their interrelations. Finally, these refinements result in guidelines or frameworks, which can function as an architecture.

This parallel process is iterative, involving a new case to solve for every cycle. Since each additional case offers a new set of premises, another generalisation process is required to ensure that new case-specific aspects are incorporated by adjusting the existing frameworks and guidelines. In other words, each iteration increases the reference data at the practical level, which thereby contribute to a gradually wider and more comprehensive architecture at the abstract level.

The UI architecture is gradually developed from a collection of UI components across all the prototypes from the different cases. The exploration of how these components might be systematically and safely placed in the user’s context through simulation and in the field has resulted in several frameworks. Finally, we considered how to structure the UIs in the user's environment according to operation and the user's situation.

# UI architecture

In developing a UI architecture that seeks to enable multivendor UI integration of maritime applications in AR, our emphasis has been on defining a set of rules and building blocks that detail what functionalities AR applications need to include and their appearance. As we did with the OpenBridge UI architecture (Nordby et al., 2019b), we looked at 1) the hardware through which UIs could be accessed, 2) the individual components of generic AR applications and 3) a system to integrate the different applications together. In this case, the UI hardware is defined as a head mounted display (HMD) AR headset such as the Microsoft HoloLens or the Magic Leap. The integration system is divided into:

1. *AR application components* that handle the kinds of information objects used to show AR information in the world.

2. *The information display system* that manages how AR components are organised in the world.

3. *AR zones* that define the way the organisation of AR components adapts to the user's position in the real world.

## AR application components

In theory, AR can display information anywhere and in any way over the real world. As a result, information display needs to be regulated in AR to make it possible for multiple applications to work together and to facilitate an adequate user experience, meaning information is displayed in ways that are predictable for the users and that are well adapted to the specificities of the user´s work environment. We defined a set of basic information objects that show various types of information in the world. These AR application components were designed to facilitate the kinds of information we have seen in our own cases and in published research about AR experiments in the maritime industry (Nordby et al., 2020).

Furthermore, we developed components that are compatible with the OpenBridge UI architecture and design guidelines (Nordby et al., 2019b, 2018). This compatibility is important because we envision AR as an extension of current workplaces and not an independent system, meaning that an application designed for OpenBridge should be accessible through the AR system as well as through traditional screens.


*Figure 2. Overview of the five types of application components currently in use in the UI architecture.*

We defined five main application component types (Figure 2): *App display*, *Widget display*, *Annotation, Ocean overlay* and *AR map.* The components offer distinct methods of information display and various systems may take advantage of their inherent affordances.

Table 1 shows how the functions of an artic vessel can be mediated to officers using the various formats. Later in this section we show the current versions of a number of the components that we have tested in our lab and onboard ships.

| | App display | Widget display | AR map | Annotation | Ocean overlay |
|---|---|---|---|---|---|
| **Arctic specific** | Convoy app | Ice pressure indicator | Satellite/drone images | Ice sheets | Ice status overlay |
| | Voyage planning tool | | Ice forecast charts | Ice bergs | Ice 3D mesh overlay |
| | AR map | | | Snowmobile | |
| **General** | ECDIS | Compass | Land | Vessels | Drawing/annotation |
| | Radar | Heading & course | Depth/safety contours | Waypoints | Safety contour |
| | Conning | Thrusters | Planned track | People | Depth |
| | Tasks / checklist | Speed | Cross track distance | Animals | Planned track |
| | Echosounder | Machine power | Waypoints | Shallow water | Cross track distance |
| | DP | Wind | Vessels | Helicopter / drone | Other vessel tracks |

*Table 1. Examples of functions that can be shown in different display formats of the AR architecture.*

## App display

Display of an application, in its entirety. For example, ECDIS or radar. In our review of cases that use AR (Nordby et al., 2020), we found two examples of the use of an app display: one was used for manoeuvring functionalities associated with conning applications (with some indication of heading, rudder angle, speed and power or load for different engines; Hugues et al., 2010); the other was used for navigation functionalities associated with ship traffic surrounding the vessel (with some indication of the position, name and heading of other ships in the area; Walther et al., 2019).

In the current version of our system, the app display is based on the OpenBridge UI libraries. The current resolutions in the HMDs are limited; therefore, there might be a need to repurpose the applications for a lower resolution than on normal screens, which could be achieved through a scaling technique such as responsive design, which allows UIs to scale to different formats. We used the OpenBridge design system that supports free scaling of the UI through responsive design principles.

## Widget display

Display of a smaller component from a full application. For example: compass, speed indicator. In our review of AR use cases (Nordby et al., 2020), we frequently found this type of visualisation, which appeared in 15 out of 19 reviewed references. As in the case for the App display, manoeuvring and navigation are the functionalities most often displayed using widgets.

The widget format helps to combine small flexible components that can be assembled in different ways throughout the UI. We designed widgets based on the OpenBridge UI libraries and used responsive design for scaling and stacking.

Figure 3 shows examples of widgets that we tested on a field study using our mixed reality platform in 2019. The first example is a combination of information usually found in a conning interface, displayed on the bow of the ship. The second example is wind information, displayed on the surface between two windows in the aft deck.


*Figure 3. Examples of widgets and a container with several widgets digitally attached to various surfaces. Above, a combination of information usually found in a conning interface, displayed on the bow of the ship. Below, wind information, displayed on the surface between two windows in the aft deck.*

## AR map

Display of location-based information on a 2D or 3D map within a frame, by default placed vertically above the horizon. Out of 19 references analysed in our AR use case review, we found three references using AR maps of the following types: a map used for navigation in a 3D isometric view (Hugues et al., 2010), a map showing the positions of other vessels in the neighbouring area of the considered ship (Mitsui O.S.K Lines [MOL], 2019) and a "velocity obstacles diagram" (Procee et al., 2018), which combines the position, heading and speed of surrounding vessels.

We found in our field studies that there is a general need to show data on a map. Because of this, we defined a simplified map information type as a basic component. We envision this area showing any map-related data and having integrated functions such as the ability to link content with real world points of interest (POIs; Figure 4). It should also be able to support various orientations such as north up or following the user´s gaze (Figure 5).

We proposed a number of concepts for AR applications that may help navigate in ice. The AR map can display the location of an object present in the user's field of view with a line connecting the real object and its location on the map (Figure 4). The map can also follow the user´s gaze, so that the contents of the map are updated depending on where the user is looking (Figure 5). We tested a concept where the AR map can be positioned in containers or be freely positioned in the space (Figure 6).

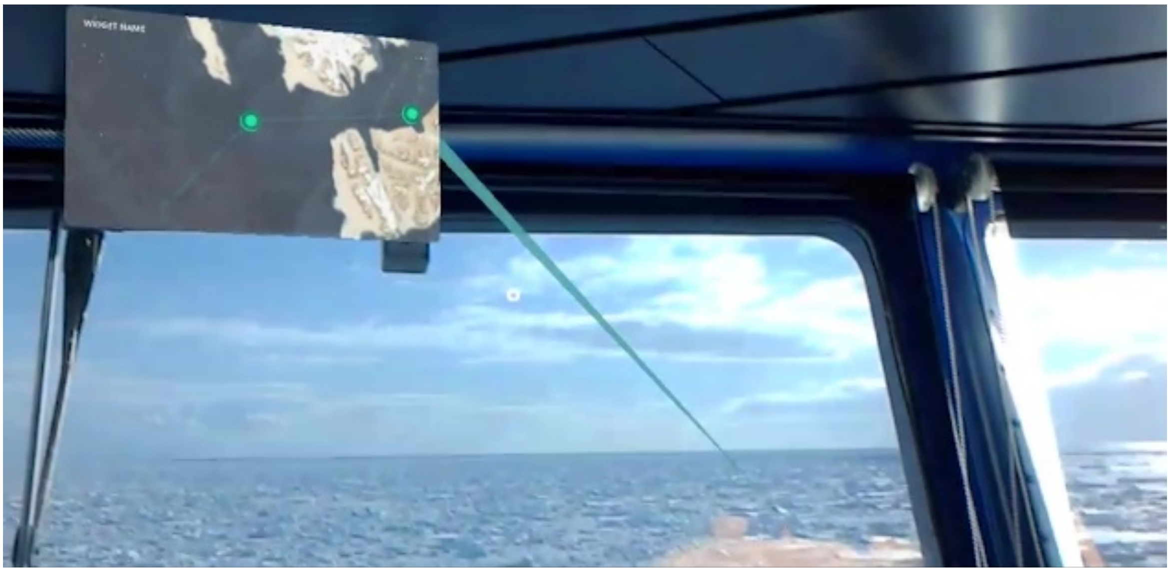


*Figure 4. AR map concept linking a point in the map with a position in the world.*

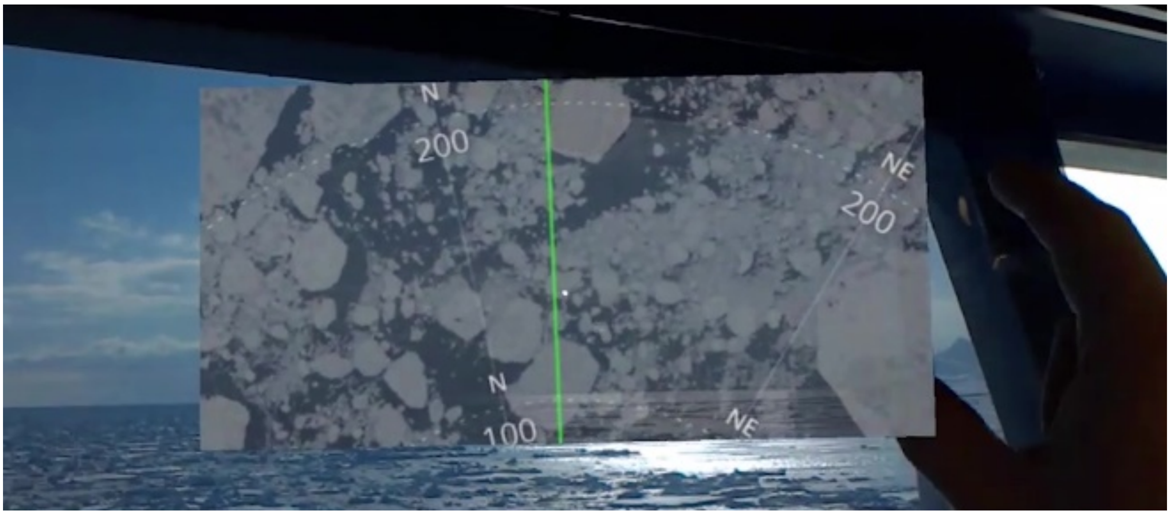



*Figure 5. AR map concept in which the map is locked to the user's head gaze direction and will rotate with user's head movements.*


*Figure 6. AR map concept of a map as a free object that can be placed anywhere, for example on a table used to plan a route through ice.*

## Annotation

The annotation format displays a small piece of information connected to a physical object in the world (a POI); for example, it might present information about a vessel present viewable from the bridge. This is a typical part of AR interfaces and we found this type of visualisation in 15 of the 19 AR publications we reviewed (Nordby et al., 2020). Annotations are often used in combination with widget displays, most commonly to display information associated with manoeuvring and navigation functionalities. They are not defined in the current version of OpenBridge. Figure 7 shows an early experiment with annotations from a field study.

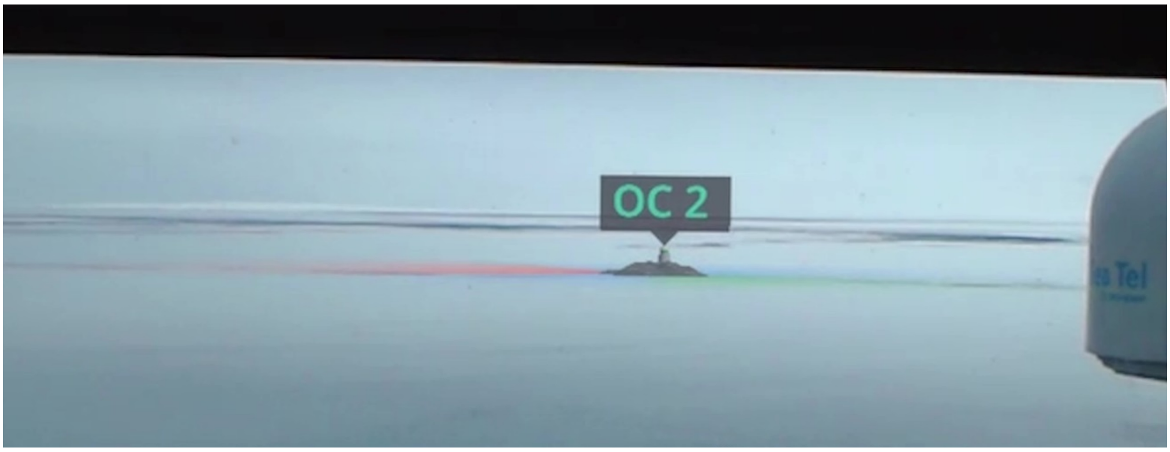



*Figure 7. Examples of annotations simulated in the mixed reality platform: a lighthouse (top), iceberg (bottom left) and neighbouring vessel (bottom right).*

## Ocean overlay

An ocean overlay displays information directly on the ocean surface so that the AR graphics match the real location of the point or area it refers to. We found this type of visualisation in 13 of the 19 references reviewed in our AR use case analysis (Nordby et al., 2020). The examples we encountered most often related to navigational functionalities, for instance, the charted route and zones to avoid displayed on the ocean surface.

## Information areas

There is a vast amount of potential information that can be placed in the world. However, there is a finite space around the users, and each type of available space affords different possibilities for information placement (Norman, 1999, 2004). Certain areas such as the water surface should have a limited overlay because it might occlude important objects like small boats. Other areas might be less critical for operation, such as the walls or the sky. A structure is needed for how AR may make use of the various affordances of the spaces around the users in a ship bridge. To define this structure, we need information areas that can be used to specify how the AR components may be distributed in the world. We have not seen any explicit description of a generic system for maritime use in previous work (Nordby et al., 2020).

In our proposal for information areas, we focus on the outside region, since this is arguably where the potential of AR is highest, yet also where the risk of obstructing the view is high. We distinguish three generic areas where AR information may be displayed, and we propose to use each area for specific application components (Figure 8). In addition, we allow the free placement of apps and widgets or app/widget containers (Figure 9). Although the proposed structure is usable in most of the cases we investigated, likely there are instances where it must be adapted to individual workplaces. This is because there might be important objects that cross the bands we have defined or other unforeseen operational requirements for the AR interface. In such situations non-occlusion areas should be defined that can be cropped out of the generic display areas.

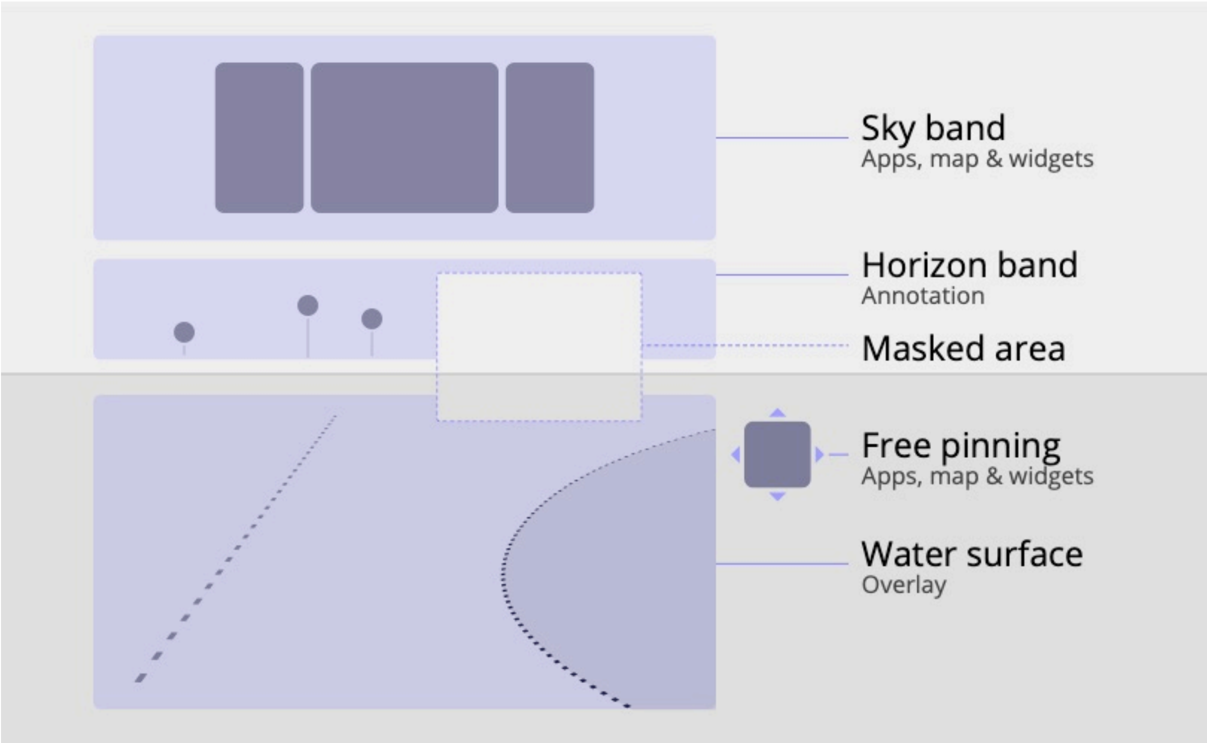



*Figure 8. Suggested information areas and the types of application components they may contain.*

The following presents each of the information areas and describes how they may affect the application components.

1. **Sky band.** The area located above the horizon should be reserved for full apps, an AR map or widgets. We propose this area since it does not occlude the ocean or the central equipment of the workplace. We envision this area being much closer to the water's surface than traditional monitors placed above the windows. As such, neck strain will most likely be less of a factor than any strain associated with screens mounted above widows. It should be possible to automatically organise the components shown in the sky according to importance and available space. The sky band can be fixed at the horizon relative to the ship or repositioned according to the direction the user is facing.
2. **Horizon band.** We propose that the area located near the horizon should only contain annotation components. We want to keep the annotations close to the objects on the water while not overlapping them. When several objects are close to each other, a system is needed to separate the various annotations so that they do not overlap even if the objects on the horizons do.
3. **Masked area.** We introduce areas where no information may be displayed based on certain rules or user input. For example, we believe that masked areas will be useful if a ship or

another important object is close to the bridge and it would be unwanted to display information on top of it.

4. **Water surface.** The area located under the horizon band should contain only ocean overlay components. This is a critical area where there is a high probability that the graphics may occlude important objects in the water. Because of this we emphasise the need to reduce information on the water and we suggest the necessity of designing efficient mechanisms that allows users to regulate information density, including control over the information layer and the ability to swiftly take away any overlay. In addition, the UI needs to be able to visually show connections between annotations and objects in the water, and between elements in the sky band and objects on the water.
5. **Free pinning**. Free pinning differs significantly from the information bands since it allows for the free positioning of AR apps, maps and widgets anywhere in the world. This includes the ability to establish container areas that function much like the horizon band and enable the structured display of AR apps, widgets and maps (Figure 9). Free pinning should be used with care to avoid information overload. Should the information displayed become too dense, the user needs to be given the control to reduce the quantity of information. To do this, each object should be easily turned on and off, and whole layers of information could be turned on and off.


*Figure 9. Free pinning of a container object with widgets attached to the back of the ship under the horizon band.*

Figure 10 offers an example of the implementation of information placement on the proposed areas in the mixed reality simulator. Notice that on this image it appears that the information container is placed inside the bridge. However, when wearing the VR headset, it is spatially positioned far away from the ship.

*Figure 10. Screenshot from the mixed reality platform with prototypes of AR applications that follow the placement rules of the information areas: the sky band with apps, widgets and an AR map (top), the horizon band with annotations (middle) and the water's surface with an ocean overlay (right).*

We are currently detailing this implementation and preparing it for formal user tests. We plan to implement the information display system in HoloLens 2 (Microsoft, 2020) in the future before we specify further the proposed information areas.

## AR zones

We observed that users need to access different types of information depending on where they are working in the bridge and how they move. In earlier research, for instance, we noticed that users often move from a workstation closer to the windows to be able to observe situations better (Nordby and Lurås, 2015). In order to accommodate users' considerable need to move freely around the bridge, we propose to divide the bridge in three types of zones (Figure 11). We suggest that the structure of the information areas as well as their informational content change as users enter and leave these zones.

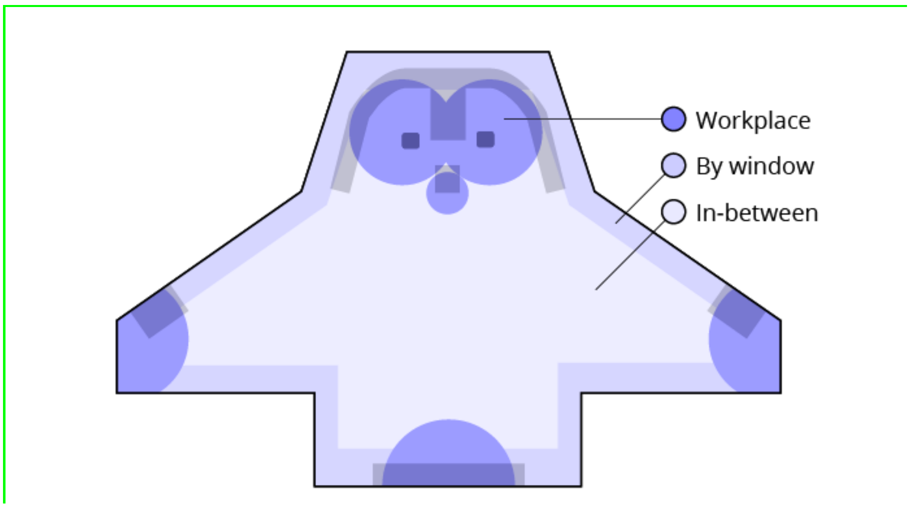



*Figure 11. Dividing the bridge into three types of zones that affect the behaviour of the AR application components.*

The *workplace* zone is centred on traditional workplaces in the bridge, such as the bridge wings or navigation station. The *by window* zone is any zone close to the windows. The *in-between* zone is any other area inside the bridge.

Informational content and areas change as users move between these zones (Figure 12). The workplace zone has information adapted to each individual workplace. In addition, we suggest that the sky band shown in Figure 8 becomes fixed to the horizon, right in front of each workplace. Apps and widgets that have been pinned by the user to support an operation or task carried out at this location appear when the user enters the zone.

We propose that the by window and in-between zones should be less rigid than the workplace zone since the physical, collaborative and operational conditions in these areas are hard to predict. Therefore, we suggest the sky band should move with the users' gaze instead of being fixed in any specific direction. In addition, we suggest that there should be a limited number of application components in use when a user is in the in-between zone since they may interfere with the work inside the bridge. Finally, we suggest no use of a water overlay and a limited use of annotations in the in-between zone, unless the user specifically asks for this information to be presented or there is a relevant alert, because the bridge itself and its content occlude the outside world significantly when the user is in the in-between zone.


*Figure 12. AR Zones: when the user goes from the "in-between" zone (top) to the "workplace zone" (bottom), the content and placement of the AR application components is rearranged.*

## Discussion

We have presented the need to develop the following frameworks to enable the safe and efficient use of AR applications on ship bridges:

1. A framework for managing the integration of AR applications into existing bridge systems
2. A framework for how multiple AR applications may share the world
3. A framework for adapting AR interfaces to changing needs

We then presented a proposal for a UI architecture with different components and rules for how the components should behave. This proposal constitutes a first step towards the development of the abovementioned frameworks. With regards to the first framework, our approach is that AR applications are an extension of existing bridge systems. In order to offer a seamless user experience, it is important that AR applications follow the same general UI design guidelines as the other screen-based UIs in the bridge. Our experiments show that an AR interface will have some components that are very similar to traditional screen-based applications and some components that are new. Thus far in our work, we see a big potential for harmonising AR design guidelines with the current OpenBridge design guidelines.

The integration of AR applications with existing bridge systems requires a re-examination of the notion of integrated ship bridge environments, because AR applications will not exist in a vacuum. We can envision, for instance, that applications on screens within the AR could be dragged using gestures or that there will be mechanisms to ensure that AR information does not overlap with screens. Further research is needed for the practical integration of AR applications with existing screen-based systems.

With regards to the second framework, our proposal offers concrete solutions for how AR applications may share the world. We proposed a standardised list of five components that follow a set of rules for what information may be displayed with each component and how the components should interact with each other. We see a need to continue this work and to focus specifically on managing information density. The current framework deals with information placement, but does not explain how to manage the density of that information based on automation or user input. The goal is to make sure that information density may be managed effortlessly by users to avoid information overload. This is important when considering the cognitive cost of AR-enhanced operations compared to the status quo (Baumeister et al., 2017).

As for the third framework of a UI architecture that adapts to changing user needs, researchers need to experiment, document and analyse the different ways in which users manage and interact with AR applications. With the implementation of AR zones, our current proposal suggests that the location of the user should automatically impact what and how information is displayed in AR. To go beyond a location-based approach, an operation- or task-oriented framework should be developed as a foundation for managing information displayed in the ship bridge. This framework could build on existing research on cognitive work analysis (Procee et al., 2017) or frequency of use (Vu et al., 2019). Another question is related to how users interact with the information. The current UI architecture proposal only addresses interaction indirectly by using the users' position for changing the interface. Other input mechanisms could include voice commands, a connection to existing generic interaction devices, eye tracking and more. Since the types of data input will vary with work conditions (Nordby and Lurås, 2015), it is necessary to develop a UI architecture that caters to different forms of input.

Finally, our current architecture only deals with visual information. Previously there has been a demonstrated use for 3D audio in ship bridges. A future framework could include 3D audio mediated through AR, making it possible to connect radio transmissions to points of interest or separating alarm channels.

## Conclusion

We presented ongoing work towards a UI architecture for maritime AR applications. We suggest AR should be seen as an extension of current ship bridge systems' interfaces. The UI architecture should be adapted to maritime use and should allow multiple systems to be accessed through AR simultaneously. We argue that the development of AR applications should be tightly connected to design frameworks that are built for an entire maritime workplace. In the case of the ship bridge, we propose to work with frameworks that 1) manage the integration of AR applications into existing bridge systems, 2) guide how multiple AR applications may share the world and 3) adapt to changing situations and user needs.

The preliminary UI architecture for AR applications presented in this paper consists of application components, information areas and AR zones that together offer an initial framework for integrating AR applications into existing bridge systems and sharing the AR space. We argue that this current proposal is a useful starting point for the further development of maritime AR applications. The UI architecture is developed in conjunction with the OpenBridge design system, which currently supports maritime screen-based applications. We suggest that the UI architecture can be an important delivery method to bring AR into the OpenBridge design system.

In future work, we will develop the UI architecture further to focus on designing for situated user views, information management and an OpenBridge UI design guideline harmonised across screen-based and AR-based applications.

## Acknowledgements

Thank you to Jon Fauske and Philip Stevju Meidell for the work on the AR prototypes and the VR platform; to all the partners of the SEDNA and OpenBridge projects; and to the crew of the KV Svalbard and Atle vessels who kindly welcomed us for several field studies. This research is part of the EU “Safe maritime operations under extreme conditions: The Arctic case” (SEDNA) project. The project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 723526.

## References

Allen, R.J. (1997), A formal approach to software architecture, PhD Thesis, Carnegie-Mellon Univ Pittsburgh PA School of Computer Science.

Baumeister, J.; Ssin, S.Y.; ElSayed, N.A.M.; Dorrian, J.; Webb, D.P.; Walsh, J.A.; Simon, T.M.; Irlitti, A.; Smith, R.T.; Kohler, M.; Thomas, B.H. (2017), Cognitive cost of using augmented reality displays, IEEE Trans. Vis. Comput. Graph. 23, pp.2378-2388. https://doi.org/10.1109/TVCG.2017.2735098

Capgemini Research Institute (2018), Augmented and virtual reality in operations: a guide for investment, No. Report MACS CS AP 20180907.

DeWalt, K.M.; DeWalt, B.R. (2011), Participant observation: a guide for fieldworkers. Altamira Press, Plymouth, UK.

Erlandsson, M.; Jansson, A. (2004), Augmented reality as a navigation aid for the manoeuvring of high-speed crafts, DS 32: Proceedings of DESIGN 2004, 8th International Design Conference, Dubrovnik, Croatia, pp.741-748.

Friedewald, A.; Lödding, H.; Titov, F. (2015), Augmented reality for the retrofit of ships, Proceedings of COMPIT 2015 14th International Conference on Computer and IT Applications in the Maritime Industries, Technische Universität Hamburg-Harburg, Ulrichshusen, Germany, pp.236-246.

Frydenberg, S., Eikenes, J.O., Nordby, K., (2019). Serendipity in the Field. Facilitating serendipity in design-driven field studies on ship bridges. The Design Journal 22, 1899–1912. https://doi.org/10.1080/14606925.2019.1594948

Frydenberg, S.; Nordby, K.; Eikenes, J.O. (2018a), Exploring designs of augmented reality systems for ship bridges in arctic waters, presented at the Human Factors conference, The Royal Institution of Naval Architects, London, UK.

Frydenberg, S.; Nordby, K.; Hareide, O.S. (2018b), Feltstudier for design av utvidet virkelighets-teknologi i navigasjon (English: Field studies for the design of augmented reality technology in navigation), Necesse 3, pp.67-70.

Giacomin, J. (2014), What is human centred design?, Des. J. 17, pp. 606-623. https://doi.org/10.2752/175630614X14056185480186

Hareide, O.S.; Ostnes, R. (2017), Maritime usability study by analysing eye tracking data, J. Navig. 70, pp.927-943. https://doi.org/10.1017/S0373463317000182

Hareide, O.S.; Porathe, T. (2019), Maritime augmented reality, Coordinates Magasine, February issue, pp.31-35.

Helle, S.; Korhonen, S.; Euranto, A.; Kaustinen, M.; Lahdenoja, O.; Lehtonen, T. (2014), Benefits achieved by applying augmented reality technology in marine industry, Proceedings of COMPIT 2014 13th International Conference on Computer Applications and Information Technology in the Maritime Industries, Redworth, UK, pp.86-97.

Hugues, O.; Cieutat, J.-M.; Guitton, P. (2010), An Experimental Augmented Reality Platform for Assisted Maritime Navigation, Proceedings of the 1st Augmented Human International Conference, AH ’10, ACM, New York, NY, USA, pp.12:1-12:6. https://doi.org/10.1145/1785455.1785467

Kvale, S. (1996), Interviews: An introduction to qualitative research interviewing, Sage Publications, Thousand Oaks, California.

Lee, J.; Lee, K.; Kim, K.; Kim, D.; Kim, J. (2010), AR-based ship design information supporting system for pipe maintenance, 11th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS, pp.607-612.

Lurås, S., Nordby, K., (2014). Field studies informing ship’s bridge design. Presented at the International Conference on Human Factors in Ship Design and Operation, 26-27 February 2014, London, UK. https://doi.org/10.3940/rina.hf.2014.05

Lurås, S. (2016), Layered scenario mapping: A multidimensional mapping technique for collaborative design, CoDesign 12, pp.133-150. https://doi.org/10.1080/15710882.2015.1072221

Lützhöft, M.; Nyce, J.M. (2008), Integration work on the ship’s bridge, J. Marit. Res. 5, pp.59-74.

Matsuo, K. (2016), Augmented reality assistance for outfitting works in shipbuilding, V. Bertram (Ed.), Proceedings of COMPIT 2016 15th International Conference on Computer and IT Applications in the Maritime Industries, Lecce, Italy, pp.234-239.

Microsoft (2020), Microsoft HoloLens 2 | Mixed Reality Technology for Business [WWW Document], URL https://www.microsoft.com/en-us/hololens, accessed 2.21.20.

Millen, D.R. (2000), Rapid ethnography: time deepening strategies for HCI field research, D. Boyarski and W.A. Kellogg (Eds.), DIS ’00 Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, ACM, New York, NY, pp.280-286. https://doi.org/10.1145/347642.347763

Mitsui O.S.K Lines (MOL) (2019), AR voyage information display system [WWW Document], URL https://www.youtube.com/watch?v=Ioepw3am-KY, accessed 11.7.19.

Nordby, K. (2019), Arctic ship bridge demonstrator for SEDNA project, unpublished report No. SEDNA D2.4, AHO.

Nordby, K.; Frydenberg, S.; Fauske, J. (2018), Demonstrating a maritime design system for realising consistent design of multi-vendor ship’s bridges, presented at the Human Factors conference, London, UK.

Nordby, K.; Gernez, E.; Eikenes, J.O.; Hareide, O.S. (2020), A review of augmented reality applications for ship bridges, Submitted to Necesse Journal.

Nordby, K.; Gernez, E.; Mallam, S. (2019a), OpenBridge: designing for consistency across user interfaces in multi-vendor ship bridges, presented at the Ergoship 2019, Haugseund, Norway.

Nordby, K.; Lurås, S. (2015), Multimodal interaction for marine workplaces used as strategy to limit effect of situational impairment in demanding maritime operations, Presented at the International Conference on Marine Design, London, UK.

Nordby, K.; Mallam, S.C.; Lützhöft, M. (2019b), Open user interface architecture for digital multivendor ship bridge systems, WMU Journal of Maritime Affairs., Volume 18, Number 2, June 2019, pp.1-22.

Nordby, K.; Morrison, A.D. (2016), Designing calm technology and peripheral interaction for offshore service vessels, Pers. Ubiquitous Comput. 20, pp.601-613.

Norman, D. (2004), Affordances and design, Unpublished article available online https://jnd.org/affordances_and_design/.

Norman, D. (1999). Affordance, conventions, and design, Interactions 6, pp.38-43. https://doi.org/10.1145/301153.301168

Procee, S.; Baldauf, M. (2014), Augmented reality as part of a man-machine interface in e-navigation, presented at the ISIS14 - International Symposium Information on Ships, Hamburg, Germany.
Procee, S.; Borst, C.; van Paassen, M.M.; Mulder, M. (2018), Using augmented reality to improve collision avoidance and resolution, V. Bertram (Ed.), Proceedings of COMPIT 2018 17th International Conference on Computer and IT Applications in the Maritime Industries, Technische Universität Hamburg-Harburg, Pavone, Italy, pp.239-249.
Procee, S.; Borst, C.; van Paassen, M.M.; Mulder, M.; Bertram, V. (2017), Toward functional augmented reality in marine navigation: a cognitive work analysis, 16th Conference on Computer and IT Applications in the Maritime Industries, Technische Universität Hamburg-Harburg, pp.298-312.
Rowen, A.; Grabowski, M.; Rancy, J.-P.; Crane, A. (2019) Impacts of wearable augmented reality displays on operator performance, situation awareness, and communication in safety-critical systems, Appl. Ergon. 80, pp.17-27. https://doi.org/10.1016/j.apergo.2019.04.013
Sanders, E.B.-N.; Stappers, P.J. (2008), Co-creation and the new landscapes of design, Co-Des. 4, pp.5-18. https://doi.org/10.1080/15710880701875068
Unity (2020), 3D Software for Architecture, Engineering & Construction [WWW Document], URL https://unity.com/solutions/architecture-engineering-construction, accessed 1.22.20.
Vu, V.D.; Lützhöft, M.; Emad, G.R. (2019), Frequency of use – the first step toward human-centred interfaces for marine navigation systems, J. Navig. 72, pp.1089-1107. https://doi.org/10.1017/S0373463319000183
Walther, L.; Schulte, B.; Jahn, C. (2019), Shore-side assistance for remote-controlled tugs, V. Bertram (Ed.), Proceedings of COMPIT 2019 18th International Conference on Computer and IT Applications in the Maritime Industries, Technische Universität Hamburg-Harburg, Tullamore, Ireland, pp.274-285.

# PUBLICATION 5

Frydenberg, S., Aylward, K., Nordby, K., & Eikenes, J. O. H. (2021). Development of an augmented reality concept for icebreaker assistance and convoy operations. Journal of Marine Science and Engineering, 9(9), Article 996. https://dx.doi.org/10.3390/jmse9090996

Journal of
*Marine Science and Engineering*

MDPI

*Article*

# Development of an Augmented Reality Concept for Icebreaker Assistance and Convoy Operations

**Synne Frydenberg [1,*], Katie Aylward [2], Kjetil Nordby [1] and Jon Olav H. Eikenes [3]**

[1] The Oslo School of Architecture and Design, 0175 Oslo, Norway; kjetil.nordby@aho.no
[2] Chalmers University of Technology, 41296 Göteborg, Sweden; katie.aylward@chalmers.se
[3] Finn.no, 0159 Oslo, Norway; jonolav.eikenes@gmail.com
* Correspondence: synne.g.frydenberg@aho.no; Tel.: +47-97613623

**Abstract:** A vessel convoy is a complex and high-risk operation completed during icebreaking operations in the Arctic. Icebreaker navigators need to continuously communicate with their crew while monitoring information such as speed, heading, and distance between vessels in the convoy. This paper presents an augmented reality user interface concept, which aims to support navigators by improving oversight and safety during convoy operations. The concept demonstrates how augmented reality can help to realize a situated user interface that adapts to user's physical and operational contexts. The concept was developed through a human-centered design process and tested through a virtual reality simulator in a usability study involving seven mariners. The results suggest that augmented reality has the potential to improve the safety of convoy operations by integrating distributed information with heads-up access to operation-critical information. However, the user interface concept is still novel, and further work is needed to develop the concept and safely integrate augmented reality into maritime operations.

**Keywords:** augmented reality; icebreaker assistance; convoy operations; navigation; human-centered design; user interface design; virtual reality-reconstructed operation scenarios; the Arctic



**Citation:** Frydenberg, S.; Aylward, K.; Nordby, K.; Eikenes, J.O.H. Development of an Augmented Reality Concept for Icebreaker Assistance and Convoy Operations. *J. Mar. Sci. Eng.* **2021**, *9*, 996. https://doi.org/10.3390/jmse9090996

Academic Editor: Apostolos Papanikolaou

Received: 13 August 2021
Accepted: 6 September 2021
Published: 13 September 2021



## 1. Introduction

Augmented reality (AR) is an emerging technology that superimposes information on top of a person's view anywhere in the environment. AR technologies can support navigation and operation on a ship's bridge by combining the real world outside the vessel with data from bridge systems [1]. However, the possibilities and premises for designing AR applications in the maritime sector are demanding to explore [2]. The spatial, physical, and temporal possibilities of this technology challenge the current practice within the field of interaction design, which up until now has been mostly screen-based [3]. In this early phase of building knowledge of how to design for AR, our aim is to develop design examples of AR applications in order to build useful design frameworks for AR which can potentially support practicing interaction designers [4]. The background motivation for designing a software application for icebreaker assistance and convoy mode derives from our design-driven field research at sea [5], where our interviews and observations with navigators demonstrated that the premises for icebreaker assistance had considerable potential for the improvement of safety for both the icebreaking vessel and the assisted vessels during these critical operations. Based on these findings, we have continued our human-centered approach with the aim of supporting the navigator to achieve enhanced control and overview during icebreaker assistance operations [6].

The AR technology is becoming increasingly viable for maritime use, particularly when information needs to be integrated during complex operations, for example, in the Arctic [7]. Maritime traffic in the Arctic is increasing, as previously unavailable shipping routes are becoming more accessible. The naturally harsh operating environment in the high north offers challenges for many shipping sectors and can have a remarkable effect on voyages. The lack of important data, such as weather reports, ice conditions, latitude errors, and varying global navigation satellite system positioning errors, makes navigational activities highly demanding, especially for navigators with little experience sailing in Arctic regions [8]. However, accurate sensor data are not enough—available data need to be presented in a way that supports mariners efficiently during demanding conditions and stressful operations. Mistakes can have major consequences, and help is often out of reach in the high north [9]. Therefore, ship bridges sailing in Arctic waters should be equipped with systems that support navigation and operations in ice.

Increased interest in and usage of passages in the high north requires an extended focus on facilitating and supporting safe operations. Icebreaker assistance in various forms is an important part of this situation, given that navigation in Arctic waters is regularly dependent on such support [10].

Icebreaker assistance is commonly divided into five specific operation types [11]: (1) vessel escorting operations involve an icebreaker breaking a channel of ice through which another vessel can follow at a particular distance, (2) breaking loose operations involve an icebreaker sailing near a vessel stuck in ice in order to release ice pressure, (3) convoy operations involve an escorting operation containing more than one vessel following, (4) double convoy operations involve two icebreakers sailing offset aligned in order to break a wider path for a broad vessel, and (5) towing operations involve towing the assisted vessel while breaking the path due to heavy ice pressure or a large amount of slush ice.

In ice-filled waters, such as the Baltic Sea, ship collisions are one of the most frequent accidents occurring during winter [12]. Convoys are one of the most dangerous and unpredictable operations during the wintertime [13]. The most crucial risk is represented by collisions between assisted vessels or between an assisted vessel and an icebreaker [12]. Relatively high speed and proper distance must be maintained during the entire operation [13]. Although crews on the icebreaker vessel recommend a certain speed and distance between assisted vessels, crews on the assisted vessels are responsible for maintaining this advice. This work can be challenging to both the icebreaker and the assisting vessel because it requires constant attention. A minor misunderstanding in communication or an operational variation can cause the vessel to deviate from the set speed and distance. Too little distance between two ships increases the risk of collision, whereas too much distance involves an increased risk of being obstructed by slush or stuck in ice [13].

According to navigators on icebreakers, experience-based rules of thumb for leading operations in a safe way are important [11]. They also emphasize the importance of systematic knowledge about operational characteristics and ship domains, including safe speed and distance according to the specific area. However, unpublished reports from field studies on icebreaker vessels conducted in the Safe Maritime Operations Under Extreme Conditions: The Arctic Case (SEDNA) project indicate that these requirements are not met optimally in the current bridge systems; navigators experience a lack of overview at several levels during icebreaker assistance operations. First, an overview of the assisted vessels is insufficient in digital bridge systems, which lack detailed key information. Second, in the physical overview outside the vessel, monitoring can be limited for other vessels during operations due to obstacles on the vessels and/or weather conditions, such as fog or darkness. Third, communication with the other vessels on very high frequency (VHF) radio may be unclear due to poor connection or language skills. A high situation awareness (SA) should be maintained for navigators leading icebreaker assisting operations by designing user interfaces (UIs) for bridge systems that take these specific user requirements into account.

The need for icebreaker assistance can arise from different situations, for instance, as a planned escort of a vessel with a lower ice class than recommended for the waters or rescuing a vessel stuck in the ice [13]. During an assisted convoy operation of several vessels, the icebreaker secures a safe passage by breaking ice at the front and leading the other vessels through the path at an appropriate distance and speed to their requested targets. The icebreaker's leading role requires careful monitoring of the other vessel's key information, as well as clear communication to safeguard the progress.

Today, external communication between vessels during convoys is transmitted through VHF radios, where ships' bridge crews exchange orders and answers. Due to potentially unstable connections and poor language skills, such forms of communication can easily lead to misunderstandings [13,14]. During a convoy operation, a misunderstanding, such as missing an order to "lower the speed to X knots," can be fatal. The internal communication on the bridge, which is an important part of Bridge resource management (a tool for safety and error management, see [15]), is particularly exposed to noise and poor system overview with data sharing during icebreaking operations. The monitoring can be supported by data from other systems, such as an Electronic Chart Display and Information System (ECDIS) or an Automatic Identification System, as well as by visual monitoring. However, accuracy and the degree of relative details of current systems are inadequate for icebreaker assistance operations; furthermore, research on the problematics of positioning in the Arctic region concludes that complementary positioning methods are required to achieve an accuracy of fewer than three meters [16]. Examples of such positioning methods are laser-based position reference systems, such as SpotTrack [17] and Differential absolute and relative position sensors, which are a dynamic positioning reference system [18]. The accuracy of the positioning affects the input data and the possibilities for developing supportive UI representations for icebreaker navigators. By UI representation, we refer to the space where interaction between the user and the systems occurs, which is either physical, such as a keyboard; or digital, such as a screen; virtual, such as an AR UI. The UI representation should be fitted to the user's situation in order to provide a sufficient overview.

Good SA is important, and in this case refers to the navigator's capability to perceive and comprehend what is going on at the bridge, in the oceanscape, and on other vessels, and the ability to project future status [19]. To maintain good SA throughout the operation, navigators need options for monitoring other vessels' speed, distance, and relative value [20]. In addition, a navigator must be able to have a full overview ahead to operate their own vessel. In the current situation, navigators need to perform a considerable amount of integration work between systems to sort and interpret key information [21]. To meet this challenge, we suggest that a convoy UI should ideally be integrated to appear from the navigator's point of view, such as by using AR technologies.

In recent years, the development of AR technologies has been rapid and market-driven, especially after the launch of head-mounted AR technologies, such as Microsoft Hololens [22]. The potential for AR in the maritime domain shows a promising outlook [23], and previous research has uncovered a range of suitable scenarios for its use on ship's bridges [3,4]. Navigator's SA and performance can be enhanced through the use of AR by functioning as an information support for navigating, regulating information overload, reducing integration work, and connecting digital and analogue information [3,23–26]. Nevertheless, research on how to involve users' needs in the design process of AR technology for the maritime domain remains limited [4]. Therefore, we argue the need to develop tools with relevant and specific data and flexible UIs that support navigators with precise information on icebreaker assistance operations, such as during convoy operations.

We approach this problem by asking the following research question: How can AR support navigators during convoy operations on ice? We answer the question by, firstly, demonstrating an example of how AR can be designed as a bridge application with the potential to support the navigator's SA during icebreaker operations. We describe and illustrate the UI concept with its functions and content. Secondly, we present a usability study of how end users have tested the application concept. The overarching approach for both the first and the second parts of this study is the application of contextual processing in a virtual reality (VR) simulator instead of on a real ship bridge [27]. This methodological approach for concept development and user testing is described in detail in the Materials and Methods section. We evaluate the concept and test, indicate limitations in the current UI concepts, and discuss further developments.

In the SEDNA project, we have investigated how we can develop safe and efficient design concepts for AR-enhanced ship bridges through a user-centered approach. This approach involves mapping and analyzing current user needs. These methods affect how the usability of new design proposals can be evaluated and how the design frameworks we continuously iterate can be generalized for the design of new AR systems. This SEDNA research builds on and extends research from previous and ongoing research projects, such as the Onsite and Ulstein Bridge Concept and OpenBridge (OB). It connects to the OB [28], where an extensive open design system is developed to make the UI design consistent on a ship's bridges across vendors and equipment. This consistency implies preset rules for fonts, sizes, placement, appearance, colors, and, to some degree, logics for functions. Currently, the OB design system includes guidelines for screens and monitors of various sizes and qualities. However, expanding the OB design system to include AR-specific design guidelines is a relevant direction to examine further. We have used the foundation of the OB design system and further developed it to function for AR in this case study, designing better system UIs for icebreaker assistance operations.

The research is part of the EU project Safe Maritime Operations Under Extreme Conditions: The Arctic Case (SEDNA) and is one of several cases developed with the aim of improving efficiency and security for vessels operating in ice-filled waters.

In the following section, we describe the method for developing and evaluating our UI concept, the results, and the challenges and advantages of augmenting an existing design system through this case study.

## 2. Materials and Methods

To investigate the potential of AR, we needed to both explore possible solutions by designing examples of application UIs and evaluate the usefulness of those solutions by conducting usability testing. Therefore, our method was twofold: the first part of the approach involved design of the AR application while the second part contained the usability testing (Figure 1). We used two different contextual approaches for our methods during the study, field studies in real context during the first phase of Method 1, then what we define as virtual reality-reconstructed operation scenarios (VRROS) (described in the following paragraphs) during the last part of Method 1 and during the whole of method 2 (Figure 1). In the following, we will describe in detail these two methods and the two different contextual approaches and how they are interlinked.

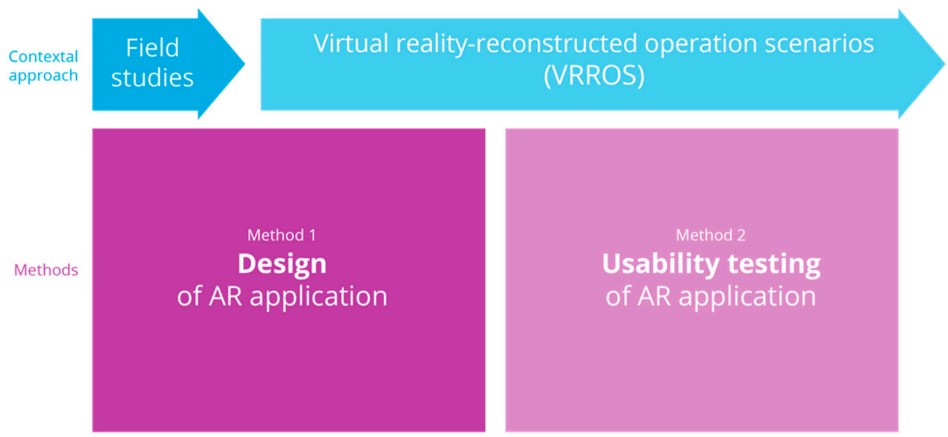



**Figure 1.** The model illustrates the twofold nature of the methods in the study, first in the left bottom square, design of AR application, followed by the right bottom square, usability testing of the AR application. On the top of the model are two blue arrows which represents the contextual approach in the two methods and the timeline of the process. The process is divided into a shorter part of field studies in the beginning of Method 1 and a longer part of virtual reality-reconstructed operation scenarios (VRROS) during both Method 1 and 2.

In Method 1, we used a human-centered design approach involving users in a way that emphasizes the human perspective throughout the research and design process [6]. For interaction design processes, creating products and services that enable users to achieve their goals in the best way possible is the main purpose [29]. In our case, supporting good SA is one of the goals. Therefore, many of the techniques and methods used for designing digital concepts, such as a bridge application, requires distinct understanding of both the use situation and the design situation [30]. By implementing two different contextual approaches throughout the study phase called Method 1 (Figure 1), we have maintained the important awareness of and distinction between the use situation and the design situation. In the following section we will describe the techniques and sub methods for design (Method 1) in this study.

The first part of our design phase was carried out in the contextual approach of field research expeditions on board several icebreakers operating and safeguarding different areas of Arctic and Baltic waters; our design process was undertaken in several stages of the project [2,3]. We used well-known field research methods, such as participatory observation [31] and co-design [32], and explored how methods and techniques for collecting quantitative data, such as eye-tracking data [33], can be used qualitatively as a digital underlay for sketching in AR and forms of rapid AR testing and prototyping [2,3]. The data captured in the field research context resulted not only in familiarization and deeper insights into the users and user situations, but also in testable ideas and concepts that were further developed in the lab.

The second part of the design phase and the usability study needed to be completed in our labs, mainly due to strict travel restriction and limited access during COVID-19 in 2020. However, UIs for ships' bridges should be designed with an emphasis on the situation in which they will be used [4]. For most designers and researchers, the Arctic maritime context is an unfamiliar setting with hard-to-reach users [34] and a demanding context to access and work in overtime [9]. In order to continuously engage with this context after the initial field studies, our process contained a continuation of the previous fieldwork onboard icebreakers within a lab setting by using what we call VRROS (Figure 2) [27]. The VRROS represent the contextual approach for our second phase of design (Method 1) and for the whole process of usability testing (method 2). The VRROS have been developed in our lab by recreating icebreaker operations in a VR-enabled simulator. The operational scenarios were designed in collaboration with and verified by usability experts and expert end users. The VRROS proved to be ideal for design development of UI concepts in the form of visual prototypes embedded in and immersed with the VR environment in the VRROS. This allowed us to rapidly test and evaluate design ideas and concepts according to a simulation of existing premises on a vessel [27,35]. In addition, the VRROS approach allowed us to maintain involvement with users, designers, and human factor (HF) specialists throughout the design and testing process.

In this study, the chosen VRROS consist of a vessel stuck in ice, requiring assistance from an icebreaker and a resulting convoy operation (Figure 2). The scenario contains a course of action from a defined start and an end with given premises, such as operations, targets, equipment, and weather conditions. A precise scenario timeline was described to achieve a high degree of realism. The detailed maritime context found in this scenario was then recreated in VR. The VR simulator is built with the Unity game engine, which can produce a realistic experience of contextual factors, such as light, weather, and icebergs, in parallel with the scenario timeline. This allows designers and researchers in the lab to test how ideas and concepts for AR technology can be applied at an early stage. The VR simulator functions as a tool for concept development and as a setting for future experimental testing of the concept.


**Figure 2.** To the left: the setup of the virtual reality-reconstructed operation scenarios (VRROS) seen from an exocentric perspective which represents the test facilitators who can monitor both the user's behavior in the room and what the user sees in the VR headset on the big screen. To the right: a screenshot of representing the egocentric perspective of what the user sees within the VRROS.

The VRROS (Figure 2) included three vessels: two cargo vessels and one icebreaker. The VR user was situated on the icebreaker ship's bridge and had an overview of the existing console screens and the AR UIs. The vessel moved according to previously recorded bridge simulator data. Thus, the user could not control the vessel but could move freely around the bridge. The bridge systems were of modern standard, with consoles and large screens displaying ECDIS and radar interfaces designed according to OB design guidelines [28] in a dusk palette. The VR scene lasted for 67 min, where the facilitator interface allowed the researcher to shift among five different chapters of the scenario timeline: (1) transit in ice, (2) break free, (3) convoy, (4) stop, and (5) loop back.

Designing for hard-to-reach environments by implementing and testing VRROS is a novel design approach. Through our studies, we were therefore simultaneously researching methodological potential. Some of the advantages were that the VRROS enabled us to isolate and concretize these separate parts of the scenario, which, from a technical perspective, could be defined as *situations*. Various premises, such as daylight, movement, and level of stress, could be set to occur during different phases of the operation within the scenarios. This allowed us to test adjustments of the AR information panes according to the current situation. Our aim is to develop designs for *situational adaptation*, which we define as UIs with which the user experiences meaningful interactions according to the situation. By developing VRROS, we can generalize a set of situations in which we can test several UI concepts, including a variety of situational adaptations, to explore how the interaction can be experienced as situated as possible. In this study, we investigated this potential by developing more operation-dedicated and situated UIs for monitoring and communicating with other vessels' icebreaker assistance operations.

The current AR hardware has optical challenges when transmitting graphics in bright environments. We demonstrated that some of these challenges can be reduced by sun-screen [35]. As technology progresses, we expect that the optical challenges will be remarkably reduced, and therefore we left the optical performance of AR technology outside the scope of this article. As a result, the figures in this article, which illustrate the AR concepts, are not optically correct but are rendered to illustrate the UI structure and functionality, given acceptable AR performance for a given context.

In this paper, we specifically describe the design proposal we developed for our own icebreaker assistance software application, containing key detailed information in strategically placed locations, filling the existing gaps in design. We focused on developing a specified mode for the application to be used during convoy operations. We developed several UI variations of the application with situational adaptations according to strategic placement in line with users' points of view, contents, functions required, and daylight modes. In the following section, we describe how we evaluated the usability of the application.

As part of Method 2, representing the usability study of the design concept is described as follows (Figure 1). Recruitment, which consists of purposive sampling, also known as judgment sampling, is a non-random technique used when a researcher needs participants to have certain qualities, skills, knowledge, or experience [36]. Purposive sampling was used to recruit participants, primarily through word of mouth, who had achieved Master Mariner certification at some point in their career and had recent experience with navigational equipment either through simulations or real life. The participants were not required to have any experience in ice navigation as this was not deemed necessary by the research team. The original plan for user testing was to recruit both fourth-year Master Mariner students and experienced navigators from Chalmers University of Technology and local shipping companies. However, the COVID-19 pandemic affected the ability to recruit and test the desired sample. The participants were therefore primarily recruited internally at Chalmers University of Technology.

The ethical considerations in this study are described in the following procedure. When the participants arrived at the test lab, they were provided with information about the SEDNA project and a brief description of the test protocol. The participants were also briefed about the potential risks related to VR use, including dizziness, nausea, and eye fatigue, and were told they could stop the test at any point. Each participant was given a unique ID number, which was used throughout the test to ensure confidentiality.

Based on the demographic data, the seven users who evaluated the scenario were professional mariners. All the participants were Swedish males. One participant was 25–34 years old, one was 35–44 years old, and the remaining five were 44–54 years old. Six participants were employed by Chalmers University of Technology, three of which were Chalmers simulator instructors. One participant was currently serving onboard and was not associated with Chalmers. All participants were considered subject matter experts in maritime navigation. In addition to demographic information, the participants were asked about their previous experiences using VR. They reported that they either had no experience at all with VR systems (four responses) or little experience using VR systems (three responses).

The equipment was set up in a VR/AR test lab located at Chalmers University. The VR hardware used in the testing was a powerful PC equipped with a GeForce 2080Ti graphic card. The VR headset used in the test was the HTC Vive Cosmos. Additional equipment required to run the usability test included a video camera, an iPad, and a large TV screen. The tools used to communicate and share information between AHO and Chalmers included Box, a VR scenario developer, Zoom, TeamViewer, and Skype.

The procedures are described as follows. A pilot study was completed prior to the official data collection to ensure that the scenario was appropriate for subject matter expert evaluation. The pilot study consisted of a walkthrough of an example scenario to identify any potential issues with both the equipment and the test procedure. This provided the opportunity to obtain preliminary feedback on the AR features and helped to develop the final test questions for the participants.

Data collection was completed at Chalmers University of Technology in Gothenburg, Sweden, in October 2020, by two HF specialists. Both HF researchers were present throughout the data collection to observe, record participants' answers, and assist with the VR controls and maneuvering through the scenario. Participants were asked about simulator sickness (dizziness, feeling unwell, nausea) multiple times throughout the testing period. No participants reported any symptoms of sickness at any point. Once consent and familiarization were completed, the participant completed a tablet-based demographic pre-test questionnaire. When finished, the researcher provided the following instructions to the user:

The overall aim of this usability test is to evaluate specific AR solutions for enhancing situation awareness for navigators on the bridge. For this test, we recreated an icebreaker and convoy scenario in VR. The vessel follows a predefined path; in other words, you are not able to control the ship. We used vessel movement data from a simulator walkthrough with the accompanying RADAR and ECDIS screens. We want you to focus on how the different AR solutions may or may not enhance your awareness of what is going on, and specifically if/how the AR solutions could lower the risk of this specific operation. The scenario is divided into five "scenes". You will get to experience each scene for as long as you want before moving on to the next scene. You can also go back to a previous scene or replay a scene. The scenario in total will take approximately 60 min. The quality and resolution of the VR headset are limited, and it might be hard to see some of the details. We assume that the AR quality will get much better, so try to imagine that the visual quality of the AR graphics is better than what you see in this test.

We want you to talk aloud during the exercise—describe what you see and how you experience/interpret what you see. We will also ask you specific questions about the different AR solutions; however, say whatever comes to mind as you experience the scenario. There is no right or wrong answer; we just want your honest opinion about the different solutions. We will ask you several times throughout the scenario if you feel sick, nauseous, or uncomfortable. We will stop the scenario if you feel unwell at any point.

The scenario began when a participant was seated and relaxed (Figure 2). The researchers allowed the participants to become comfortable on the virtual bridge. Most of the time, as they explored the bridge, a discussion about the UI concept emerged naturally. If the participants did not initiate a discussion themselves, they were prompted by the researcher. The UI concepts tested in the usability study are listed below (Table 1) and further described in the results.

**Table 1.** Elements of the UI concept and elements of feedback.

| UI Concept | Elements of Feedback |
|---|---|
| Information pane (Figure X—point to results photo) | Content of UI<br>Ability to interpret information<br>Size, placement, and color<br>Potential risks<br>Usefulness of the UI<br>Is any critical information missing? |
| Icebreaker assistance mode (Figure X—point to figure in results—same for below concepts) | |
| Convoy mode | |
| Points of interest | |
| Aft bridge UI | |

A mixed-methods approach was adopted to collect and analyze the data. The focus was primarily on qualitative data obtained through a think-aloud protocol. Think-aloud methods allow participants to talk out loud or verbalize their thoughts while completing a specific task [37]. Both concurrent and retrospective verbal reports were completed throughout the data collection. The concurrent report involved the participants speaking out loud throughout the scenario as they encountered a specific AR solution. They spoke about what they saw and were probed with pre-determined specific questions about each AR feature if needed. The retrospective verbal report was completed post-scenario and required the participants to reflect on their experiences. They were asked to recall any additional comments or feedback about either the AR features or the VRROS experience.

In addition to the think-aloud protocol, HF specialists observed the participants throughout the entire scenario. The test setup allowed the researchers to have the same view as the participants through the TV screen while also observing their body language and movements (Figure 3). Any interesting observations were noted and added to the participants' testing sheets.

**Figure 3.** VR/AR test setup at Chalmers University, showing one of the users wearing the VR headset and using portable controllers to interact and move around on the virtual ship bridge.

In terms of quantitative data, two questionnaires were developed using the software SurveyMonkey [38]. A basic demographic questionnaire was administered at the beginning of the test day, which captured the user's demographics, previous VR experience, and AR expectations. A post-test questionnaire was administered at the end of the test day, which asked specific questions about the usefulness of the AR technology and attempted to obtain a quantitative assessment of the user's overall experience using the technology.

The qualitative data were analyzed by two HF specialists who were present during the data collection. This process was followed to provide a cross-check system to ensure that the data were correctly interpreted. The data were first transcribed individually by each HF specialist, and then the transcripts were compared for consistencies or discrepancies. Once the researchers were satisfied that the transcripts reflected reality, both the individual participant transcripts and a summary of the comments about each AR widget were delivered to the design team. The questionnaire data were analyzed using basic Excel functions to summarize the demographics and the post-test questionnaire results.

## 3. Results

The results are presented in two separate parts. First, we present the results from the human-centered design process of developing a design example of the AR application Icebreaker assistance. Second, we present the results from the usability study, which assessed each AR UI mode, in addition to the users' perceptions of the overall usefulness of this application during icebreaking operations.

### 3.1. Concept of Icebreaker Assistance and Convoy Mode

We developed a software application called Icebreaker Assistance. The application is integrated into an information pane consisting of several other UI components used in combination during icebreaker operations, such as conning data and radar. The information pane can be integrated into the user's environment in several ways, for example, by fixing its position to a wall, on top of a window, or so that it can move around with the user. The application aims to support navigators in monitoring the status and relation to nearby vessels during icebreaker assistance. We envision the application to be relevant for use during several operations related to icebreaker assistance, such as when navigating in close distance to other vessels, such as during escort, towing, or breaking loose a vessel stuck in ice. The application can also be envisioned as a support in other situations apart from icebreaker assistance, such as rescue operations, inspection or other customs inspections at sea, or in entering/leaving trafficked harbors.

The application builds on the UI architecture of OB that describes how to design maritime graphical UIs [39] and current research expanding the OB framework into AR [4]. The illustrations in this article are represented in the palette for dusk light conditions. In the following section, we present the research process.

#### 3.1.1. Information Pane

During icebreaker operations, the information pane is assembled by information components for the navigator's situated needs during icebreaker assistance, containing their own ship information, thrusters, map, and, highlighted in the red square, Icebreaker assistance (Figure 4). The Icebreaker Assistance application can consist of the information pane, however also has other individual appearances adapted to the situation, such as pinning of information to other vessels or as a translucent application mode placed close to windows on the bridge.

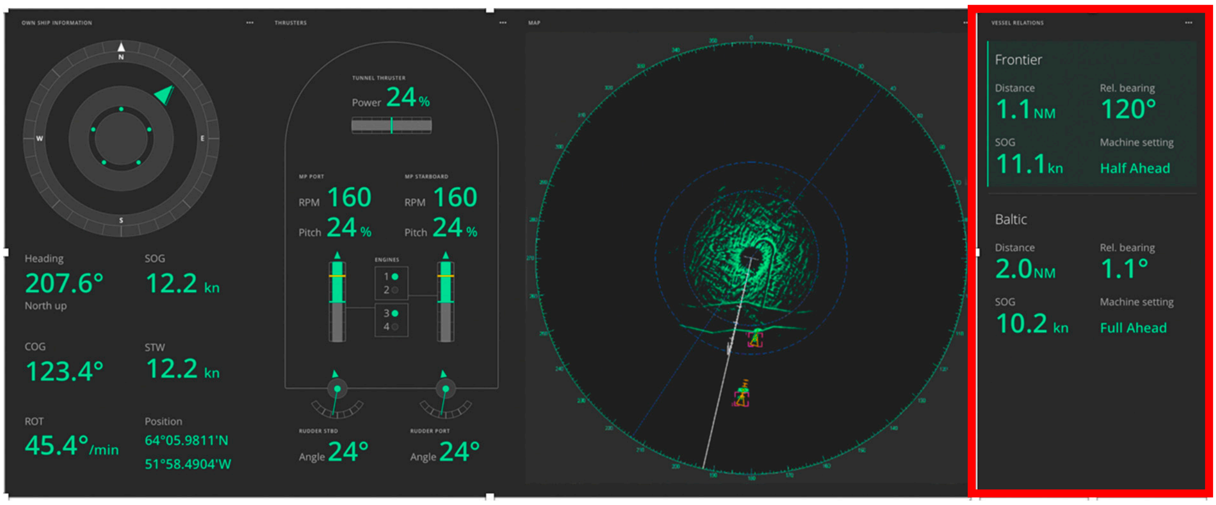



**Figure 4.** Information pane, consisting of an assembly of information components used during icebreaker assistance operations with the icebreaker assistance application marked in the red square.

#### 3.1.2. Icebreaker Assistance Mode and Convoy Mode

In the general mode of the Icebreaker Assistance application, the names of related vessels are represented in addition to their current distance, relative bearing, speed over ground, and machine setting (Figure 4). Convoy mode is a specialized mode used during a convoy operation (Figure 5). The assets of convoy mode are useful in convoy operations of three or more vessels for monitoring the relations between vessels 2 and 3 (and possibly 3 and 4), where the vessels should have clear awareness of eventual alterations in speed and distance around other vessels. The specialized mode for convoys is activated when vessels enter a convoy operation and are ready to start (Figures 5 and 6).

The desired ideal speed and distance between the vessels can be set by the navigator. The distance between the vessels must not be too narrow due to the risk of collision; however, it must also not be too wide due to potentially heavy ice pressure that can force the ship to shrink.

Above are the participating vessels in the convoy, as represented by icons placed vertically in the existing order with vessel name to the left and speed over ground to the right. The distances between the vessels are represented by the distance to the left, relative speed over ground to the right, and are additionally supported by vertical arrows between the ships that indicate differences in speed.

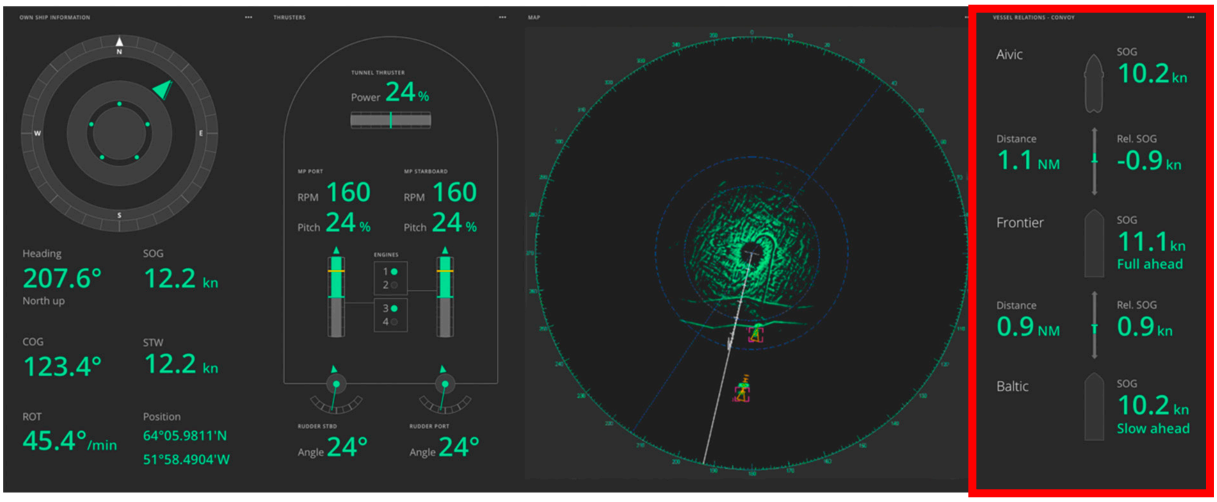



**Figure 5.** Information pane with convoy mode in the application Icebreaker Assistance marked in the red square.

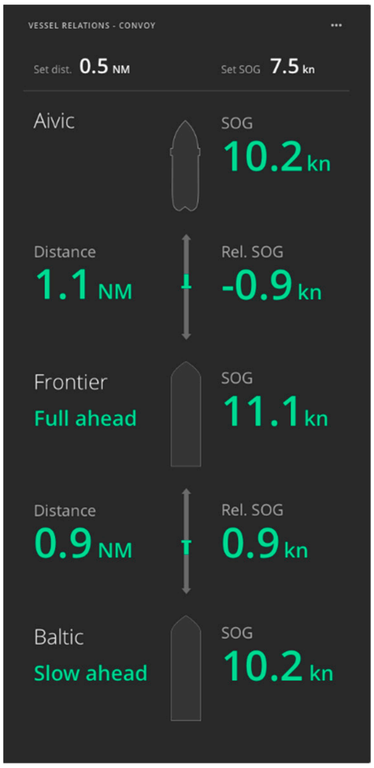



**Figure 6.** Close-up illustration of the Icebreaker Assistance application UI in convoy mode.

Engine settings for all vessels are included in the widget to allow navigators on the leading vessel to monitor other vessels' capacities and whether they are following instructions correctly. In Figure 5, the engine settings for the vessel Frontier are indicated by *Full ahead*, and, for the vessel Baltic, *Slow ahead*.

### 3.1.3. Appearances and Placement

The application consists of several representations with various options for appearance and placement, depending on the situation. For the usability test, we tested three different representations: points of interest (POIs), aft bridge information pane, and the large information pane. In the following section, we describe and illustrate the two additional representations.

In icebreaker assistance mode, pinning information about POI, such as other vessels, in the outside view by the navigator to keep track of their critical information can be relevant. The pinning function of POIs represented by vessels nearby is illustrated in Figure 7. By default, a vessel is represented by a symbol in a circle, where the arrow indicates the heading of the other ship relative to the AR user's position. The symbol changes color from green to orange and then to red as the ships get close to each other to alert the user about the risk associated with close proximity between the vessels. When gazing at the symbol, more information appears: distance, (relative) bearing, closest point of approach (CPA), and time to CPA. Subsequently, the user can pin the information pane to keep it open or to add it to a widget, for example, by using a voice command, a specific gesture, or a control button, as used in the usability test. The POI information outside looks the same in regular mode and convoy mode.

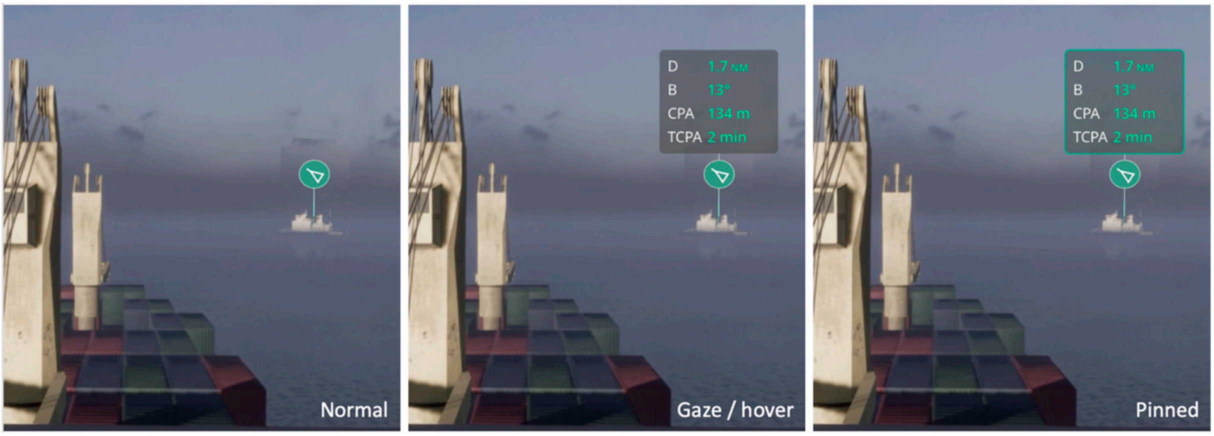



**Figure 7.** Function of pinning vessels by gazing.

In both modes, the navigator may gain access to the icebreaker assistance UI when moving around on the bridge. The application can be independently displayed in AR while looking backward from the aft bridge (Figure 8). As exemplified in Figure 8, which is a photo mockup designed to illustrate how the UI would appear in use, exploring areas without function, such as window bars, can be useful.

With the Icebreaker Assistance application, we see several possible UI representations in AR that can be adapted to the situation in a seamless way that can support a navigator's situational awareness. However, to begin validating the application proposal as a concept, we chose to evaluate the proposals described above in a usability test.

### *3.2. Usability Test of the Application*

In the following section, we present a usability study of the current versions of the design proposal for the Icebreaker Assistance application, conducted in a virtual demonstrator by professional mariners. The results are presented from both the think-aloud protocol and the questionnaire.


**Figure 8.** Use of convoy mode in Icebreaker Assistance separately displayed on the aft bridge in a photo-realistic mockup.

#### 3.2.1. Results of the Think-Aloud User Test

Tables 2–4 summarize the results from the concurrent think-aloud protocol.

**Table 2.** Participant feedback from the UI setup (information pane).

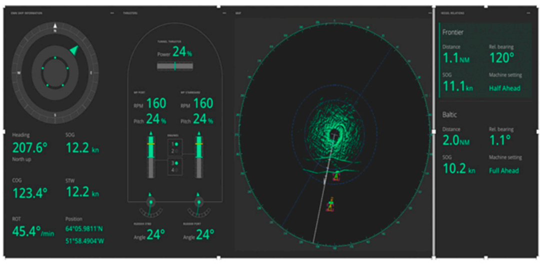
| Information Pane | Participant Feedback |
|---|---|
|  | Participants like that the information pane moved with them around the bridge. This could improve SA. |
| | Participants liked having the radar on the panel, this was very useful for ice operations. |
| | Panel was intuitive and clear and had useful information and a good color scheme. |
| | Participants suggested to not add any more information to this panel, as this could risk information overload. |
| | Opinions differed on what information is the most important and where it should be placed. In general, participants liked the way it looked. |
| | Participants liked the ability to switch between VRM and convoy mode. |
| | Operator should have the opportunity to customize the information on the panel by choosing what information is visible and where it is placed on the panel. |
| | Participants suggested slightly increasing the size of the labels (primarily to the left of the engine panel). |
| | Participants suggested slightly lowering the placement of the panel. They noted the possibility of having neck pain from looking up too much. |

**Table 3.** Participant feedback from POI appearance and placement.

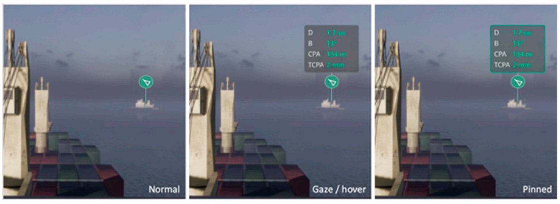
| POI Appearances/Placement | Participant Feedback |
| --- | --- |
|  | POI information panel had relevant information, and the participants liked that the panel could be locked and was visible "through the walls". |
| | POI changing colors made sense, but the arrow was not intuitive. What the arrow was pointing at and why was difficult to interpret. |
| | Participants suggested adding speed to the information panel above the POI, which was agreed to be the most crucial information for this operation. |
| | Participants suggested adding more information about the vessel which the operator could choose to see (e.g., speed, name of the vessel [AIS information]). |
| | When the vessels were close to each other, the panels overlapped, which sometimes caused confusion. |

**Table 4.** Participant feedback on the vessel relations and convoy modes.

| Vessel Relations/Convoy Mode | Participant Feedback |
| --- | --- |
|  | Extremely useful and intuitive function in a convoy situation. This will help with the communication of important information to other vessels. |
| | Participants would like this convoy panel to be available at all places on the bridge and to be able to put it up when needed. |
| | Arrows in the middle with the small green symbol were very hard to see. Participants suggested to change their color or enlarge and clarify them. The idea is good but difficult to understand, given the small size. |
| | Participants suggested a color change in the presence of "danger;" if the vessel POI is red, perhaps the information in the panel/convoy mode should also be red, yellow, etc., to align both images together. |
| | Participants suggested not adding any more information to this panel to avoid overcrowding. |
| | Having machine settings in this panel is very valuable. Obtaining accurate information is currently difficult, as it is mostly from observing the other vessel. |

#### 3.2.2. Results from the Retrospective Verbal Reports

The following list provides a summary of the retrospective reports from the participants. This was collected after the participants completed the scenario and had a chance to reflect on the experience and provide a higher-level perspective of the purpose and use of these solutions in icebreaker and convoy operations:

- Overall, the participants had a positive attitude toward the AR solutions and observed clear benefits for its use in a convoy scenario in ice-covered waters;
- The participants believed that these solutions could improve safety in icebreaker and convoy operations;
- The participants strongly advocated that these types of solutions must be flexible and customizable for individual operators and for specific operations (e.g., convoy). Convoy operations require the navigator to constantly look out the windows at other ships and down at the ice to observe the distances between vessels. The only information that should be presented during this part of the operation is data that can help the operator safely complete the operation. When the vessels are lined up in the convoy, an option to obtain the most important information should be available;
- The participants agreed that this technology could improve SA. This concept allowed them to maintain a heads-up position to monitor the outside world, paired with important vessel information, which was more integrated than in real life;
- Several participants mentioned the importance of avoiding information overload. This was generally tied to the ability to turn the AR widgets on/off when needed;

- All participants agreed that the standardized design of the navigational information (OB UI) used in the test was positive and should be implemented on board;
- The participants brought up interesting aspects of how this technology and test setup could be used for training, particularly for less experienced operators. Given the complexity of convoy operations on ice, using VR as a tool to provide cadets with exposure to this type of situation would be very beneficial.

#### 3.2.3. Results from the Post-Test Questionnaire

In terms of the overall experience, five participants reported “very positive”, and two reported “positive” on a five-point scale from “very negative” to “very positive”. When asked “What is your attitude toward the value of using AR solutions for navigation?” in the pre-test questionnaire, the participants responded very positively both pre- and post-test. Only one participant changed their perspective on the value of AR solutions after testing them toward a more positive attitude. Six out of seven participants believed that AR solutions were either very valuable or extremely valuable for navigation, and one participant believed they were somewhat valuable. This is to be expected, given the already positively skewed responses prior to testing the AR solutions.

Figure 9 provides a summary of the results of the remaining five questions in the post-test questionnaire. The results show a positive experience and attitude toward the use and application of the AR UI. Only one participant did not agree that there is a clear benefit to using AR solutions for navigation. Additional comments provided by the participant indicate that their hesitancy stems from the possibility of over-reliance on the AR information and the potential for information overload.

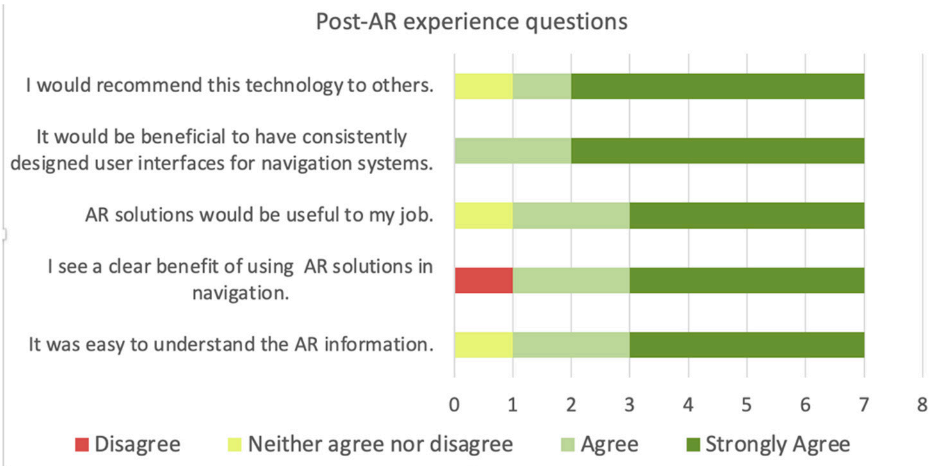



**Figure 9.** General questions about AR solutions that were part of the post-AR experience.

## 4. Discussion

In this paper, we present a concept showing how an AR UI can be designed to support icebreaker and convoy operations in ice. Although the usability study shows promising results, the application concept is premature from a design for new technology perspective, and further research is needed to determine if the app concept can actually support icebreaker operations by improving usability, efficiency, and safety. However, the rationale behind this study is to develop an evaluable example. In the following sections, we discuss some quality factors that we believe are important to highlight in regard to the research question.

Coordinated vessel data are an important usability issue. Relevant data from several vessels in a uniform UI setup make it easier to monitor all ships at the same time. The navigator will be spared from having to do demanding integration work between systems to compare key data, such as speed, heading, and propulsion. An icon representation of the vessels in the correct order makes the UI comparable to a real-world situation. The relative values between each vessel are a new parameter that the application offers, which navigators must manually calculate today. Furthermore, a coordinated application, such as icebreaker assistance, can reduce the need for verbal communication between the icebreaker navigator and the supported vessels. Today, the primary mode of communication is via VHF radios, even though they are associated with a high risk of miscommunication and misunderstanding [40]. The proposed application can transmit key data, information, and commands, thereby reducing the risk of misunderstandings and improving communication between team members to help obtain shared situation awareness. A shared SA can be defined as a shared understanding of a situation among team members at one point in time [41].

A convoy scenario is a specific type of operation that could directly benefit from coordinated vessel data and improved shared SA. As an example, during user testing, one of the participants who had extensive real-world experience in ice navigation spent most of the time looking out the bridge wing windows away from the main control station. He indicated that experienced ice navigators focus on the visuals, feel of the vessel, feedback from the engines, and ice movements according to ship movements. Normally, this navigator would rely on their colleagues to report the numerical information necessary to fully understand the situation while also clearly reporting their personal understanding of the situation. This information loop is at risk of miscommunication and misunderstanding. The application would allow the navigator to stand on the bridge wing to look out the window while also being able to see the status and distance to nearby vessels in all situations when multiple vessels are close to each other, along with others present on the bridge. In addition, we propose that all the vessels in the convoy should have access to the application and the coordinated vessel data, which would further promote a shared SA between all vessels and increase the transparency of decision making.

Situation-based UIs have the potential to improve usability. The concept demonstrates a situation-based adaptation of the application by dividing it into two different modes, representing the stages of the operation. We suggest that the modes are manually set by the user. The number of modes could potentially be increased if user needs in the different stages of the operation proved to be remarkably different. We also suggest that modes for critical stages in an icebreaker operation, such as breaking another vessel free from ice, might need an individual mode with a UI setup adapted to high levels of stress. This implies removing unnecessary information and perhaps enabling multiple output modes, such as voiceover for critical data. We suggest that designing applications with several situational modes for complex and sequence-based operations, such as icebreaker assistance, can be a way to support the operation and increase safety. The application also adapts to the user situation by offering different UI representations adapted to different user zones in the bridge. User zones, also referred to as AR zones, refer to a sectioning of the bridge (or workspace) based on physical, spatial, and conditional characteristics, such as poor or good view of a certain element, and user needs, such as the need to monitor another system or handling devices [4].

What impact on safety can applications, such as Icebreaker Assistance, have? The maritime industry is technology driven [42], and ensuring that new technology will support the operator rather than introduce unwanted risk is important. When asked about safety, the participants agreed that highlighting various types of critical operational information at the right time could improve safety. Furthermore, the participants believed that the UI concept could improve their SA through the ability to maintain a consistent lookout while having access to critical information. When asked if these UI concepts could reduce the risk of a convoy-related accident, six out of seven participants agreed that the risk of an accident would be reduced, and one participant was torn between the benefits and risks of the technology.

Identifying the risks is important, given that integrating AR technology in maritime operations has potential safety concerns. This matter was one of the post-test questions that was discussed with the participants. In general, the participants raised concerns about the possibility of information overload, especially in high-traffic areas. They indicated that the only way that this technology could be used safely is for the user to have the ability to turn it on and off, and the ability to remove the headset whenever needed.

Furthermore, some of the UI representations caused confusion for the participants. One example was the POI arrow symbol indicating another ship (Figure 6). All participants had varying ideas of what this represented and determined that it was not easy to understand, which could lead to a risk of distraction. This reiterates the importance of user testing and user involvement in the early stages of the design process for the application to be able to quickly adapt solutions to user needs [23]. Finally, in some parts of the scenario, the information overlapped, which the participants noted as something that should be avoided as much as possible. Displaying one information layer at a time should be possible to reduce confusion. Overall, these safety concerns are minor and can easily be adapted in the design phase through the feedback process adopted in this study. New technology always poses risks; however, the potential safety benefits of this technology seem to outweigh its potential risks.

Several limitations have affected the method. User testing was completed during the COVID-19 pandemic. This caused adaptations to the test protocol, including safe distancing and increased sanitation practices. Furthermore, COVID-19 restrictions caused a reduction in participant availability, resulting in a relatively small and homogeneous sample size. However, for usability studies, five test persons have been cited as enough to find most of the usability issues with a product, with any more leading to an observation of repeated results [43,44]. Data saturation was experienced during the final stages of the scenario testing, which led the researchers to finalize the data collection. Although it is a widely used method, the think-aloud protocol has some limitations. This method has been criticized for its ability to capture participants' genuine thoughts about the activity, given individual personality traits, and the ability to verbalize thoughts in a research setting [37]. An additional challenge with this method is ensuring that participants feel comfortable being honest and potentially critical about their reflections. Although challenging, the test setup and participant group in this study decreased the influence of these limitations. The participants in this study were seafarers who were trained in talking through their thought process for decision making in critical situations, meaning the think-aloud protocol was somewhat natural for them. Furthermore, the distribution of the research team between Oslo and Gothenburg allowed the HF specialists conducting the test and the AR architects and designers to operate independently, which was clearly communicated to the participants. We believe that this setup helped the participants feel comfortable in criticizing the scenario, as the researchers who were present at the data collection were not responsible for developing the solutions.

Another important issue we would like to bring into the discussion is the effect that a consistent UI architecture has on usability. The UI concept presented is designed to be a part of a consistent UI design for all ship bridge workplaces. Design consistency is an important quality for UIs because it improves a user's ability to switch and transfer competence, logic, and skills between different UI units and across various systems [45]. Given that AR equipment will be used with existing workplaces, we believe that it should share characteristics with other interfaces on the ship's bridge. To achieve such consistency, we built the AR UI on the OB design system, an open-source platform that enables various vendors to develop cost-effective, safe, and efficient UIs for the maritime domain. One of the core goals of OB is to achieve improved design consistency across a workplace assembled by systems from multiple vendors [39]. The design system is in continuous incremental development through several industry-driven research projects. This form of the standardization of navigational equipment seems to show obvious advantages for both vendors and users, as the registration rate for using the OB system is continuously increasing.

The AR interface development has adapted components for OB to AR and produced results that will be used to extend OB guidelines to cover AR applications. This is an important contribution, given that limited precedence exists in research and practice on how to design AR interfaces for ships. The proposed design cases will help build better knowledge of AR solution space for maritime applications.

Furthermore, the use of VRROS for concept development and testing is a novel approach for design development. In this study, AR UIs were realized in VR to develop and test AR concepts. Interpreting and adapting the OB design system to work for AR is challenging, both in terms of development and testing, for several reasons. Accessibility to the user context is limited. It is highly necessary to conduct field work to develop and test AR prototypes, given that they closely connect to the physical context. The use context has rapidly changing conditions, which alter the premises for design. Finally, conducting design processes within the user context is very demanding.

The VRROS provide the opportunity to overcome several of these challenges with its easy access and manipulatable conditions, and a far less demanding environment to design within. In addition, access to perform usability testing had a far lower threshold than testing in real conditions. The methodological approach of performing virtual fieldwork through the use of VRROS was also tested on master's students at AHO due to COVID-19 measures in Autumn 2020 and tends to have high efficiency for quick prototyping and evaluation of UI ideas. Despite the efficiency of virtual fieldwork and testing, we would like to emphasize that we believe that development and usability testing in a real-world context would most likely have revealed several other relevant requirements and problems with the design that needed to be tackled. As such, we see the VRROS approach as a complementary addition to real-world design development and usability testing.

Throughout the testing, the participants were asked about their experience of testing AR UIs in VR. Most of the participants were skeptical at first, given their limited knowledge of and exposure to VR technology. However, once acclimated to the VR environment, all the participants recounted a positive experience, with no feelings of malaise at any point throughout the study. This resulted in a high level of user acceptance of VR to evaluate the UI concepts. In addition, every participant commented on the high-quality visuals and overall realistic feeling of being on the bridge. Immersive technologies, including virtual reality, AR, and mixed reality, are becoming more viable options for maritime education and training [46]. This study provided a positive experience, and as the technology improves, immersive technologies will likely become even more affordable and available for maritime research.

Regarding further development of the concept, the Icebreaker Assistance app concept is incomplete, and several aspects need to be explored, defined, and further developed. Some examples that are planned to be further developed include the activation of convoy mode; a convoy planning tool; distributed representation of data, alerts, and notifications; the use of the application in other situations.

## 5. Conclusions

In this article, we present a design concept and usability study of an AR application called Icebreaker Assistance, which supports convoy operations on icebreaker vessels. The work adopted new VR scenario-driven design and test methods. The purpose of the study was to explore and evaluate how AR UIs can be designed to support icebreaker operations and improve navigator safety. We demonstrated and user-tested a novel UI design that adapts the UI representations according to where the user moves on the bridge.

The AR concept tested in this study shows promising potential to improve safety during convoy operations in Arctic waters. The AR concept has the ability to integrate currently distributed information, decrease the chance of miscommunication within and between vessels, and possibly improve operator SA. The participants remained cautiously optimistic about the further development of AR UIs, indicating that the potential risks of information overload and distracting visuals should not be underestimated. This study presents an initial concept development and small-scale usability study that can be used to establish a foundation for evaluation and further research.

**Author Contributions:** Conceptualization, J.O.H.E., K.N. and S.F.; methodology, S.F., K.A., K.N. and J.O.H.E.; software, J.O.H.E.; validation, J.O.H.E., K.N.; formal analysis S.F., J.O.H.E., K.N., K.A.; investigation, J.O.H.E., S.F., K.A. and K.N.; resources, K.N.; data curation, K.A.; writing—original draft preparation, S.F., K.A.; writing—review and editing, K.N., J.O.H.E.; visualization, J.O.H.E.; supervision, K.N.; project administration, K.N.; funding acquisition, K.N. All authors have read and agreed to the published version of the manuscript.

**Funding:** The research presented in this paper was funded by the EU project SEDNA. This project receives funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 723526.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Informed consent was obtained from all the subjects involved in the study.

**Acknowledgments:** We would like to thank the project team of the EU project SEDNA, who have provided valuable knowledge and contributions in realizing the design concepts and usability testing across several campuses. We also give thanks to the participants in the user test who shared their knowledge and experience in their evaluations.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## References


1. Grabowski, M.; Rowen, A.; Rancy, J.-P. Evaluation of wearable immersive augmented reality technology in safety-critical systems. *Saf. Sci.* **2018**, *103*, 23–32. [CrossRef]
2. Frydenberg, S.; Eikenes, J.O.; Nordby, K. Serendipity in the field. Facilitating serendipity in design-driven field studies on ship bridges. *Des. J.* **2019**, *22*, 1899–1912. [CrossRef]
3. Frydenberg, S.; Norby, K.; Eikenes, J.O. Exploring designs of augmented reality systems for ship bridges in arctic waters. In Proceedings of the Rina—International Conference on Human Factors, London, UK, 26–27 September 2018.
4. Nordby, K.; Etienne, G.; Frydenberg, S.; Eikenes, J.O.H. Augmenting OpenBridge: An open user interface architecture for augmented reality applications on ship bridges. In Proceedings of the Computer Applications and Information Technology in the Maritime Industries, COMPIT'20, Online Conference, 9–10 August 2020.
5. Luras, S.; Nordby, K. Shaping designers' sea sense: A guide for design-driven field research at sea. In Proceedings of the Marine Design 2015, London, UK, 2–3 September 2015.
6. Giacomin, J. What is human centred design? *Des. J.* **2014**, *17*, 606–623. [CrossRef]
7. Laera, F.; Fiorentino, M.; Evangelista, A.; Boccaccio, A.; Manghisi, V.M.; Gabbard, J.; Gattullo, M.; Uva, A.E.; Foglia, M.M. Augmented reality for maritime navigation data visualisation: A systematic review, issues and perspectives. *J. Navig.* **2021**, *74*, 1073–1090. [CrossRef]
8. Røds, J.-F. *Navitagtion in the Arctic. How Can Simulator Training be Used for Assessment and Reduction of Risk?* The Arctic University of Norway: Tromsø, Norway, 2018.
9. Rogers, D.D.; King, M.; Carnahan, H. Arctic search and rescue: A case study for understanding issues related to training and human factors when working in the north. In *The Interconnected Arctic—UArctic Congress 2016*; Springer Science and Business: Berlin/Heidelberg, Germany, 2020; pp. 333–344.
10. Topaj, A.; Tarovik, O.; Bakharev, A.; Kondratenko, A. Optimal ice routing of a ship with icebreaker assistance. *Appl. Ocean Res.* **2019**, *86*, 177–187. [CrossRef]
11. Rosenblad, M. *Increasing the Safety of Icebound Shipping—WP4 Operative Environment (Icebreaker Operations)*; Helsinki University of Technology: Espoo, Finland, 2007.
12. Banda, O.; Goerlandt, F.; Montewka, J.; Kujala, P. Winter navigation at the Baltic Sea: An analysis of accidents occurred during winters 2002–2003 & 2009–2013. In *Safety and Reliability, Methodology and Applications*, 1st ed.; Nowakowski, T., Mlynczak, M., Jodejko-Pietruczuk, A., Werbinska-Wojciechowska, S., Eds.; Taylor & Francis Group: London, UK, 2015; pp. 83–92. [CrossRef]
13. Goerlandt, F.; Montewka, J.; Zhang, W.; Kujala, P. An analysis of ship escort and convoy operations in ice conditions. *Saf. Sci.* **2017**, *95*, 198–209. [CrossRef]
14. Buitendijk, M. Assumptions and Poor Communication Lead to Vessel Collision SWZ Maritime. SWZ Maritime. Available online: https://www.swzmaritime.nl/news/2021/03/10/assumptions-and-poor-communication-lead-to-vessel-collision/ (accessed on 10 June 2021).
15. Oconnor, P. Assessing the effectiveness of bridge resource management training. *Int. J. Aviat. Psychol.* **2011**, *21*, 357–374. [CrossRef]

16. Yastrebova, A.; Hoyhtya, M.; Boumard, S.; Lohan, E.S.; Ometov, A. Positioning in the arctic region: State-of-the-art and future perspectives. *IEEE Access* **2021**, *9*, 53964–53978. [CrossRef]
17. Kongsberg, M. Laser-Based Position Reference System. Available online: https://www.kongsberg.com/no/maritime/products/vessel-reference-systems/position-systems/laser-based-position-reference-system/ (accessed on 14 June 2021).
18. Kongsberg, M. Differential Absolute and Relative Position Sensor, DARPS. Available online: https://www.kongsberg.com/no/maritime/products/vessel-reference-systems/position-systems/differential-absolute-relative-position-sensor/ (accessed on 14 June 2021).
19. Endsley, M.R. Toward a theory of situation awareness in dynamic systems. *Hum. Factors J. Hum. Factors Ergon. Soc.* **1995**, *37*, 32–64. [CrossRef]
20. Jussila, J.; Lehtonen, T.; Laitinen, J.; Makkonen, M.; Frank, L. Visualising maritime vessel open data for better situational awareness in ice conditions. In Proceedings of the 22nd International Academic Mindtrek Conference, New York, NY, USA, 10–11 October 2018. [CrossRef]
21. Lützhöft, M.; Nyce, J. Integration work on the ship's bridge. *J. Marit. Res.* **2008**, *5*, 59–74.
22. Microsoft HoloLens. Mixed Reality Technology for Business. Available online: https://www.microsoft.com/en-us/hololens (accessed on 21 June 2021).
23. Gernez, E. Human-Centered, Collaborative, Field-Driven Ship Design: Implementing Field Studies for The Design of Ships in Operation. Oslo School of Architecture and Design. Available online: https://aho.brage.unit.no/aho-xmlui/handle/11250/2608505 (accessed on 8 June 2021).
24. Baldauf, M.; Procee, S. Augmented reality in ships bridge operation. In Proceedings of the ISIS 2014—International Symposium Information on Ships, Berlin, Germany, 27–28 September 2018. Available online: https://www.researchgate.net/publication/273057248_Augmented_Reality_in_Ships_Bridge_Operation (accessed on 13 April 2018).
25. Hareide, O.S.; Porathe, T. Maritime augmented reality. *Coord. Mag.* **2019**, *15*, 31–35.
26. Procee, S.; Borst, C.; Van Paassen, R.; Mulder, M. Using augmented reality to improve collision avoidance and resolution. In Proceedings of the 17th International Conference on Computer and IT Applications in the Maritime Industries, Pavone, Online Conference, 28–30 October 2021. Available online: https://repository.tudelft.nl/islandora/object/uuid%3A42f31d3a-d18b-41b9-9b09-bf1c0643a96c (accessed on 17 February 2021).
27. Aylward, K.; Dahlman, J.; Nordby, K.; Lundh, M. Using operational scenarios in a virtual reality enhanced design process. *Educ. Sci.* **2021**, *11*, 448. [CrossRef]
28. Nordby, K. OpenBridge Design Guideline. Available online: http://www.openbridge.no/guideline.html (accessed on 22 February 2021).
29. Siang, T. What is Interaction Design? The Interaction Design Foundation. 2018. Available online: https://www.interaction-design.org/literature/article/what-is-interaction-design (accessed on 28 June 2021).
30. Luras, S.; Nordby, K. Field Studies Informing Ship's Bridge Design at the Ocean Industries Concept Lab. In Proceedings of the Human Factors in Ship Design & Operation, RINA, London, UK, 26–27 February 2014.
31. De Walt, K.M.; De Walt, B.R. *Participant Observation: A Guide for Fieldworkers*; Rowman Altamira: Lanham, MD, USA, 2011.
32. Sanders, E.B.-N.; Stappers, P.J. Co-creation and the new landscapes of design. *CoDesign* **2008**, *4*, 5–18. [CrossRef]
33. Hareide, O.S.; Ostnes, R. Maritime usability study by analysing eye tracking data. *J. Navig.* **2017**, *70*, 927–943. [CrossRef]
34. Lurås, S.; Lützhöft, M.; Sevaldson, B. Meeting the complex and unfamiliar: Lessons from design in the offshore industry. *Int. J. Des.* **2015**. Available online: http://www.ijdesign.org/ojs/index.php/IJDesign/article/view/1845 (accessed on 21 September 2017).
35. Eikenes, J.O. How to Create Your own HoloLens Sun-Screen by Jon Olav, H. Eikenes. Ocean Industries Concept Lab Medium. Available online: https://medium.com/ocean-industries-concept-lab/how-to-create-your-own-hololens-sun-screen-68c466071a01 (accessed on 8 June 2021).
36. Etikan, I.; Musa, S.A.; Alkassim, R.S. Comparison of convenience sampling and purposive sampling. *Am. J. Theor. Appl. Stat.* **2016**, *5*, 1–4. [CrossRef]
37. Fan, M.; Shi, S.; Truong, K.N. Practices and challenges of using think-aloud protocols in industry: An international survey. *J. Usability Stud.* **2020**, *15*, 85–102.
38. SurveyMonkey. SurveyMonkey: The World's Most Popular Free Online Survey Tool. Available online: https://www.surveymonkey.com/ (accessed on 21 June 2021).
39. Nordby, K.; Frydenberg, S.; Fauske, J. Demonstrating a maritime design system for realising consistent design of multi-vendor ship's bridges. In Proceedings of the Conference on Human Factors, Orlando, FL, USA, 21–25 July 2018.
40. Aylward, K.; MacKinnon, S.N.; Lundh, M. Preventing unruly technologies in maritime navigation: A systems approach. In *Advances in Intelligent Systems and Computing*; Springer Science and Business: Berlin/Heidelberg, Germany, 2020; pp. 421–428.
41. Salas, E.; Prince, C.; Baker, D.P.; Shrestha, L. Situation awareness in team performance: Implications for measurement and training. *Hum. Factors J. Hum. Factors Ergon. Soc.* **1995**, *37*, 123–136. [CrossRef]
42. Aylward, K.; Johannesson, A.; Weber, R.; MacKinnon, S.N.; Lundh, M. An evaluation of low-level automation navigation functions upon vessel traffic services work practices. *WMU J. Marit. Aff.* **2020**, *19*, 313–335. [CrossRef]
43. Nielsen, J.; Landauer, T.K. Mathematical model of the finding of usability problems. In Proceedings of the INTERACT'93 and CHI'93 Conference on Human Factors in Computing Systems, Amsterdam, The Netherlands, 24–29 August 1993; ACM: New York, NY, USA, 1993; pp. 206–213. [CrossRef]

44. Nielson, J. *Why You Only Need to Test with 5 Users*; Nielsen Norman Group: Fremont, CA, USA, 2000. Available online: https://www.nngroup.com/articles/why-you-only-need-to-test-with-5-users/ (accessed on 15 November 2020).
45. Nielsen, J. Coordinating user interfaces for consistency. *ACM SIGCHI Bull.* **1989**, *20*, 63–65. [CrossRef]
46. Mallam, S.C.; Nazir, S.; Renganayagalu, S.K. Rethinking maritime education, training, and operations in the digital era: Applications for emerging immersive technologies. *J. Mar. Sci. Eng.* **2019**, *7*, 428. [CrossRef]

# PUBLICATION 6

Frydenberg, S., & Nordby, K. (2022). Virtual fieldwork on a ship's bridge: Virtual reality-reconstructed operation scenarios as contextual substitutes for fieldwork in design education. *Virtual Reality*. Advance online publication. https://doi.org/10.1007/s10055-022-00655-1

Virtual Reality
https://doi.org/10.1007/s10055-022-00655-1

S.I. : COVID-19

# Virtual fieldwork on a ship's bridge: virtual reality-reconstructed operation scenarios as contextual substitutes for fieldwork in design education

Synne G. Frydenberg[1] · Kjetil Nordby[1]

Received: 1 March 2021 / Accepted: 22 April 2022


## Abstract
Designing for professional, high-risk user contexts often implies limited accessibility for interaction designers to conduct field research and field testing, and the measures taken by most universities in Norway in 2020 to prevent COVID-19 spread have further contributed to the problem of achieving the contextual insight needed throughout the design process by severely restricting travel for research purposes. In this paper, we describe the use of virtual reality-reconstructed operation scenarios (VRROS) for Arctic-going vessels implemented in support of and as a substitute for the contextual aspects of fieldwork in the education of master's students studying interaction design. The virtual reality rig contains three scenarios contextualizing ships' bridges and their surroundings originally developed for research on designing navigation and operation applications using augmented reality technology. We evaluate whether aspects of the VRROS can substitute for real fieldwork by evaluating students' use of the VRROS using a student questionnaire. Finally, we discuss the value and potential of using VRROS as a supplement and support when studying how to design for hard-to-reach contexts in the future.

**Keywords** Virtual reality-reconstructed operation scenarios · VR simulator · Contextual support · Interaction design education · Fieldwork · Augmented reality

## 1 Introduction

Design-driven fieldwork is an important component in user-centered design processes for complex professional domains, such as the maritime (Lurås and Nordby 2014). Gaining knowledge of and working on a given problem within its context is key for professionals alongside students to acquire the ability to reflect *in* action and *on* action (Schön 1984). Testing and prototyping in context are important in the educational modules offered by the Ocean Industries Concept Lab (OICL) and in our research practice. As researchers and teachers in the Master of Design program at the Oslo School of Architecture and Design, we aim to facilitate different forms of fieldwork in all courses. However, the many measures taken to fight COVID-19 spread restricted all forms of fieldwork in 2020.

To overcome the challenges represented by the fieldwork restrictions, we leverage what we define as virtual reality-reconstructed operation scenarios (VRROS) of Arctic-going vessels running in our virtual reality (VR) lab as a contextual substitute. The VRROSs were developed in our previous EU project, SEDNA—Safe Maritime Operation Under Extreme Conditions: The Arctic Case (referred to as SEDNA), which centered on various aspects of safe and efficient maritime operations in the Arctic. We further framed the assignments to match the three VRROSs of Arctic-going vessels playing out realistic events and operations in detail scenarios. Hence, the students could benefit from the potential to gain a situational understanding and a tangible sense of scale, space, and time in the ship's bridge environment that the VRROS offered.

The students' group work in the VRROS resulted in two generally important learning outcomes for them. First, the students were achieving a common tangible understanding and experience of the context they were working with by familiarizing themselves with physical, spatial, and temporal

✉ Synne G. Frydenberg
synne.g.frydenberg@aho.no

Kjetil Nordby
kjetil.nordby@aho.no

[1] The Oslo School of Architecture and Design, Oslo, Norway

aspects in the scenarios. Second, they explored efficient ways to prototype and evaluate design concepts. In addition, regarding the strict COVID-19 measures, the students' work in the VR lab counteracted the isolation they experienced because of learning remotely and brought them into a physically and virtually shared working situation in which they could discuss and try out meaningful and logical interaction design concepts. Therefore, we argue that VRROS potential for doing design-driven virtual fieldwork for both students and practitioners should be further examined. Our research question (RQ) is: *How can aspects of design-driven fieldwork be substituted with the VRROS used in a VR simulator?* We answer this question by first presenting and evaluating the use of three VRROSs of Arctic-going vessels played out in detail and simulated in VR as a substitute for real student fieldwork during a six-week module. Second, we evaluate a questionnaire asking seven open-ended questions to determine how the students reflected upon their learning outcomes and VRROS usage. Finally, we discuss the potential of using VRROS in education and practice.

This study centers on OICL research from the following research projects: 1) the EU-funded project SEDNA, which has focused on developing an innovative and risk-based approach to safe Arctic navigation, ship design and operations (SEDNA-project.eu 2017; Nordby et al. 2020), 2) the Open VR project, targeting the next generation of virtual reality for human-centered ship design, and 3) the OpenBridge project, where an open-source platform for development of software for safe and efficient workplaces is under development (Nordby et al. 2018).

## 2 Background

### 2.1 Design-driven field research

Safety–critical workplace design is a demanding field for both students and professional designers. In our research on the maritime domain, we uncovered several reasons for this. First, most safety–critical workplaces restrict third-party access, which makes the context and the users difficult to reach (Lurås and Mainsah 2013). Second, for most designers, the working context of a vessel—spanning offshore vessels to icebreaker vessels and coastguard vessels to fishing trawlers—is highly unfamiliar (Lurås 2016). Changing weather conditions and complex operations, constitutes an unpredictable and challenging workplace for the field researchers as well as the crew (Nordby and Lurås 2015). However, understanding the users of a safety–critical workplace requires insight into good seamanship and the high levels of complexity in their use of advanced technology to perform tasks (Lurås and Mainsah 2013). The ability to systematize premises and user requirements for the complicated bridge systems used during complex operations and under demanding conditions depends on high maritime domain awareness (Lurås and Nordby 2015). Therefore, to design safe and efficient solutions that support navigators' situational awareness in safety–critical workplaces, such as on ships' bridges, a designer needs to fully understand—and preferably personally experience—the implications that contextual factors have for the user's situation (Frydenberg et al. 2018).

Previous research projects in the OICL have proposed an approach for acquiring experience and knowledge specifically for designers working within the maritime field called *design-driven field research* (Fig. 1). The approach contains three main aspects of field research: 1) *design reflection*, which implies the reflection and mental process of developing design ideas while in the field; 2) *experiencing life at sea*, which implies gaining familiarization with and insight into the context, the situations, and the people; and 3) *data mapping*, which implies the collection of raw data.

### 2.2 Related work

The practical approach of applying, developing, and evaluating concepts and processes as a continuous learning process for a specific context is important in some other fields. The term *virtual fieldwork* has multiple interpretations; it can be used as a term for conducting web-based research techniques, such as netnography (Mkono 2012) or for understanding qualitative research (Mejias 2017). However, the perspective of the internet as a virtual site differs in meaning from the physical context like we refer to. Systems for conducting virtual fieldwork of physical sites have been established as exploratory learning environments for practicing excavation in archaeology (Getchell et al. 2010) and for digital landscape architecture (Rekittke et al. 2021). Domains such as geology and geography have implemented several forms of virtual fieldwork, such as for professional development programs for teachers to familiarize with and investigate field sites in geoscience teacher education (Granshaw and Duggan-Haas 2012), as smartphone-driven virtual reality applications for use by geography students jointly

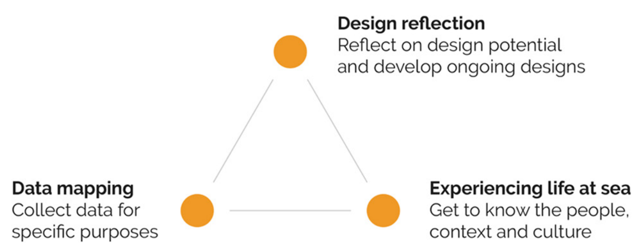



**Fig. 1** Model for design-driven field research representing a triangulation between the aspects of design reflection, experiencing life at sea, and data mapping (Lurås and Nordby 2014)

with physical fieldwork (Minocha et al. 2018), and as virtual field experiences of relevant locations based on drone images for students in introductory geology courses (Dolphin et al. 2019). Within engineering, virtual fieldwork has been implemented for virtual access in remote situations, such as virtual field trips for students to achieve insight for designing industrial scale plants (Seifan et al. 2019), virtual laboratories supporting traditional hydraulic engineering learning (Mirauda et al. 2019), and immersive virtual fieldwork in the petroleum industry (Gonzaga et al. 2018).

Virtual field studies on public displays have been used for evaluating public displays and found to be a powerful research tool (Mäkelä et al. 2020). However, implementing virtual fieldwork in developing AR applications using virtual reality worlds is rare and has been suggested to be particularly suitable for indoor environments without other people (Gushima and Nakajima 2021). Besides Gushima and Nakajima's recent conference paper describing this approach, we believe that only a few examples explore virtual fieldwork for designing AR.

## 3 Method

This study is based on a case study of a design education module that was implemented with an ad hoc approach to accommodating the drastically changed premise of teaching due to COVID-19 restrictions. The case study was based on two methods: student project documentation and a questionnaire. The first dataset was the students' project documentation from their projects containing images, videos, keynote presentations, and written documentation. The second data set was based on the questionnaire comprising seven unstructured questions reflecting upon the students' learning outcomes and VRROS usage.

### 3.1 The teaching module

*Cross-Situational Design Patterns* is the name of a six-week module held by the OICL at the Oslo School of Architecture and Design. A total of 15 (five male) students participated in the module. The participants had somewhat different educational backgrounds before entering the course, spanning industrial and interaction design to visual communication and fashion design; thus, they possessed different background knowledge, skills, and assumptions regarding how they approached virtual fieldwork.

In this module, the students had three shorter projects with the aim of exploring multimodal design patterns for AR to be used by navigators on an Arctic ship's bridge. By design patterns, we refer to solutions to interaction design problems in a specific context (Tidwell et al. 2020). The *solutions* should be developed as design concepts for an interface between the navigator and ship bridge systems. The students should use the specific *problems* from the assignment descriptions (listed below) to decide on a narrow and specific problem area, such as making an AR widget design for the representation of other vessels in the oceanscape (Scenario 1). The students defined whether the design concept was intended to work as a replacement or as an add-on to the existing ship bridge systems. For the three projects, different written scenarios alongside VRROS were given to the students to represent the *context*. In the following, we list a summary of the scenario with the belonging assignment:

1. **Scenario 1—The Grounding of Vega Sagittarius:** In this scenario, a container vessel departing from the port of Nuuk, Greenland, runs aground on a submerged rock after its sudden change of course to avoid drift ice.

   Assignment: *How can a user interact with a point of interest (POI) in the oceanscape? The type of POI (for example, another vessel) should be decided by the student.*

2. **Scenario 2—The sinking of the MV Explorer:** In this scenario, an expedition vessel entering an ice field in Antarctica collides with an underwater iceberg and sinks.

   Assignment*: How can interactions for regions of interest (ROIs) be designed? The ROIs should represent different types of ice conditions.*
3. **Scenario 3—Convoy:** In this scenario, an icebreaker vessel rescues two cargo ships stuck in the ice by breaking them free and leading them into a convoy until they reach secure waters.

   Assignment: *How can the user assess risk proximity during navigation and operation regarding fixed or moving objects in the immediate vicinity? Assessment of risk proximity could be either in the planning phase, during the breaking free phase or during the convoy.*

The intended purpose of the solutions should be to improve the safety and efficiency of the navigator's interaction with the ship bridge systems. To learn more about the premises for this, the students had several lectures with field experts and relevant literature supporting their background knowledge. The premise for their design solutions was to use Microsoft HoloLens as a mediating technology to design for (Microsoft HoloLens 2021). The students were encouraged to use the VRROS to familiarize themselves with the current scenario and work with a prototyping method with which they thought they could best convey the user experience to the rest of the class to understand and evaluate the usefulness of the design solution concept.

### 3.2 Virtual reality-reconstructed operation scenarios

The VRROSs were developed in a recent research project exploring the use of AR technology in Arctic navigation (SEDNA), where the purpose of the scenarios was to produce a realistic 3D modeled context wherein we could design and test new AR concepts (Frydenberg et al. 2021). We recreated three different scenarios containing icebreaker operations using a VR-enabled simulator. The scenarios were partly developed based on facts and data from some selected real shipping accidents and operations, such as the sinking of MV Explorer in the Antarctic Ocean in 2007 and convoy operations in the Bay of Bothnia. The detailed scenario descriptions were constructed by a multidisciplinary research team—spanning navigators to human factors engineers to interaction designers—to quality-check different aspects, such as realism in some events during the operations and applicability for exploring improvements.

The VRROSs were realized as dynamic 3D model scenes using the Unity game engine (Unity 2020) with an attached HTC Cosmos VR headset. The VR system was powered by a personal computer with an NVIDIA 3090 game card (NVIDIA 2021). The simulation was run on a steady 90 fps, and we did not receive any reports of nausea from the users. We removed buoyance on the ship to reduce the chances of the user getting wave-induced motion sickness during the scenario.

The three different VRROSs have slightly different contents according to which scenario they represent. They all comprise a main vessel where the VRROS user is situated (see Fig. 2), alongside other vessels and environmental volumes and surfaces, such as icebergs, rocks, and ice floes in the oceanscape. The VRROS allows the user to move freely around the entire virtual ship's bridge by teleporting or moving physically in the tracking space. The VRROS plays through the prescripted timeline of the scenario, comprising some events. The main vessel has a determined route and actions with which the VRROS user cannot interfere with. However, by altering the user interface (UI) on the bridge and experimenting with new AR UIs, the VRROS offers possibilities for experiencing the UIs in realistic contexts in ways that were not possible in a training simulator. Altering the UIs directly in the VRROs requires some knowledge of using the Unity game engine. Therefore, we asked the students to make recordings from the scenarios and use Adobe After Effects software to add visual layers on top of the recording to simplify the prototyping process of the new AR UIs they created (Adobe 2021). Hence, they could also add recordings of a user interacting with the graphics to convey the overall concept to the class.

Although the ship bridge is unpopulated, this setup enabled the students to familiarize themselves with the ship bridge's physical, spatial, and temporal properties during the scenario timelines. Adding to the possibility of moving around on the bridge, the students could manipulate visual conditions such as the amount of daylight (bright, day, dusk, and night), waves and weather conditions in addition to time. Potential motion related to changing conditions is removed due to high risk of motion sickness for the wearer of the VR equipment. The students could do a simple manipulation of the scenario, such as jumping through time and triggering AR functions from a control screen, while a user was immersed in the VR scene. They could test their UI concept in different conditions by asking themselves questions: "What if the situation was characterized by heavy motions from waves, will this design concept work then? If not, how can we better adapt it to be used during wavy conditions?" or "What if the situation was characterized as night with no natural light and the need for maintaining a good night vision is important for the user, will this design concept work then? If not, how can we better adapt it to be used during night conditions?" This form of cross-situational testing of design concepts induced the exploration of the many variations and adaptions needed in the work of designing AR UIs for ship bridges. Followingly, this manipulation of conditions back and forth increased the students' awareness of the need for situational adaptation.

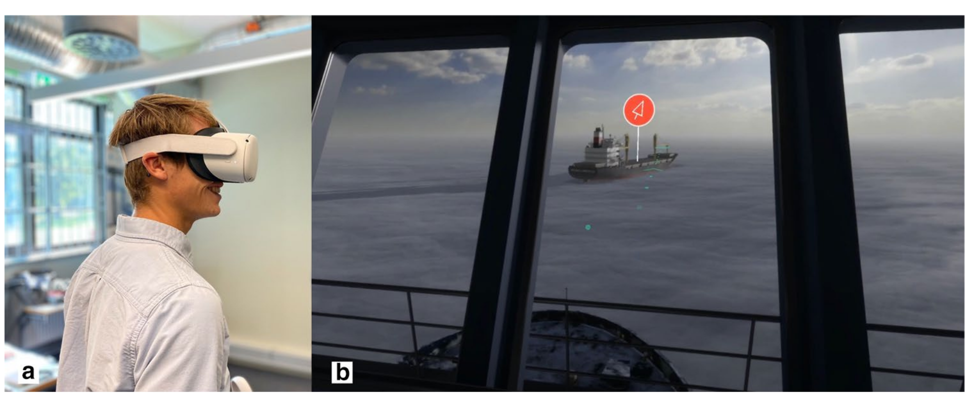



**Fig. 2** The virtual reality-reconstructed operation scenarios (VRROS) setup. **a** shows a student using the headset to access the VRROS. The rest of the participants can see what the user sees in the VR headset on a big screen. To the right: a screenshot from the what the user experiences in 3D modeled world representing the VRROS

### 3.3 The students' use of VRROS

The students started with a self-organized familiarization period with the VRROS. This period was guided by four of the students who had received special supervision in learning the features and possibilities for manipulation of the VRROS in advance. In addition, a student assistant from the OICL lab and one of the teachers offered supervision upon demand.

Two of the students did not test the VRROS, while the thirteen other students used the VRROS in varying degrees during the three projects. The students' use of the VRROS was documented using their own images, videos, and presentations from 15 different projects. In addition, each student produced an individual final report that documented the projects they had participated in alongside their reflections. From this sample, we selected examples that demonstrate the various findings presented in the result section. We analyzed these data based on a model of design-driven field research to isolate the different aspects and further used the RQ to filter out the aspects of design-driven fieldwork for which the VRROSs have functioned as a substitute.

### 3.4 The questionnaire

The questionnaire's open-ended questions were part of a final exam where the students documented, reflected upon and discussed the learning outcomes associated with the module. Table 1 shows the part of the exam from which the answers represent the second sample for this article (Table 2).

We analyzed the questionnaires using coding (Robins et al. 2009). To categorize the responses, we flagged each response with a color code representing a thematic category,

**Table 1** The student questionnaire comprising seven open-ended questions

| Write an overall reflection on what you have learned in this module. Some questions you should include in your reflection: | |
|---|---|
| 1 | Did you accomplish what you expected (how/why not)? |
| 2 | How did you approach working with a complex user context? |
| 3 | How did you use VRROS to understand the complex user context? |
| 4 | How valuable and how useful was access to the context through the VRROS? |
| 5 | How did you approach working in a new technology (if you worked with AR/VR)? |
| 6 | How did you relate to working within the time constraints imposed on developing each project? |
| 7 | How did the COVID-19 measures affect your work? |

**Table 2** The table lists the learning concepts (Anderson et al. 2001) in the left column. The middle and the right columns reveal different aspect within each of the learning concepts that can be facilitated through either design-driven virtual fieldwork or design-driven field research (Lurås and Nordby 2014). The table displays the different qualities in each method

| Learning concepts | Design-driven virtual fieldwork | Design-driven field research |
|---|---|---|
| Creating | Rapidly explore concepts and prototypes in virtual context | Explore concepts in real world situations |
| | Develop high-fidelity design | Develop low-fidelity design sketches |
| | Create complex design patterns | Co-create with users |
| Evaluating | Undisturbed decision making | Reflecting on designs |
| | Checking standards | Implement and collect data from real user tests (lower frequency) |
| | Implement simulated user tests (higher frequency) | |
| Analyzing | Easy access and full control over the situation to organize, differentiate, restructure, and relate elements | Ad-hoc analysis while collecting data |
| | | Full analysis done after the field study |
| Applying | Low threshold for testing | Higher threshold for testing due to situational constraints and lack of equipment |
| | A/B testing | |
| Understanding | Familiarizing with the physical (partly), spatial, and temporal aspects of the context | Ethnography, user insight |
| | | Familiarizing with the physical (partly), spatial, temporal, social, and emotional aspects of the context |
| | | Embody experiences |
| | | Combinations of sensory input |
| Remembering | Conveying realistic design concepts by simulation on demand or by generating high-fidelity videos | Raw data (Video recordings, sound recordings, images) |

such as representing an experience like "I found it challenging," "I adapted," or "I learned," or as answers within spans from "not at all," "to some extent," and "to a wide extent". The list of codes was developed while reading the responses, thereby allowing us to customize the codes according to the responses and adjust them accordingly.

### 3.5 Limitations and strengths of the methods

Neither method provided reliable or replicable data. Our roles and biases as teachers most likely affected our interpretation of the results, as we knew far more about what each student had achieved and about their experiences than what they expressed through their answers in the questionnaire and in their project documentation. Further, the students were instructed to answer each question in one or two sections of continuous reflection. However, some responses were deficient, mixed together with another question or did not answer explicitly the question. This limits the full basis of the response.

The strengths of the methods were their low cost and effort. Further, they yielded a fair amount of data that, rather than playing a validating role toward answering the RQ, functioned as descriptive to develop a new approach to teaching. The totality of these descriptive data forms an interesting and—in our situation of strict and ongoing COVID-19 measures—relevant reflection on how education can adjust to the new travel restrictions and on whether such solutions can even contribute to giving immersive fieldwork methods an extended value.

## 4 Results

In the following, we present a summary of the data we collected based on the students' use of the VRROS and the questionnaire.

### 4.1 The students' use of virtual reality-reconstructed operation scenarios

Many of the student groups leveraged the VRROS. They did this in often unexpected and innovative ways. In this section, we will present examples of how the students integrated the scenarios into their creative processes.

#### 4.1.1 Familiarizing themselves with the use context and the technology

The students used VRROS to familiarize themselves with the physical, spatial, and temporal aspects of having the ship's bridge as a working context. None of the students had been on a real ship's bridge before. Their search for insight into the user's surroundings by inspecting potential areas, surfaces, and perspectives suitable for design ideas seemed to fuel their concept development, both for quality and quantity. In addition, few of the students had previous experience with using or designing for AR. Therefore, their synchronized familiarization with both the virtual use context they were going to design for (the VRROS) and the technology they wanted to design with (Microsoft HoloLens) appeared to have a constructive effect. Figure 3 shows a group of students switching between the two modes of familiarizing themselves with the user context employing the VR simulator to access the VRROS and in addition exploring the nature of AR interaction by testing the Microsoft HoloLens (Zeller et al. 2019).

#### 4.1.2 Using video recordings from VRROS as raw material in design visualizations

Having familiarized themselves with the use context, the students made scenario recordings by selecting the viewer's placement and perspective on the bridge, contextual conditions, and time slots in the scenarios that they found relevant for applying their design ideas.

To illustrate this, we will describe an example from the third project working with risk proximity in scenario 3. The group explored how AR interfaces for placing vessels in a convoy could be designed (Fig. 4). In the project presentation, the group demonstrated their exploration by showing a selection of videos made by combining recordings from the VVROS, graphics, and recordings of a user interacting with the graphics, all put together and animated in After Effects. Their concept conveys a UI setup in which the icebreaker navigator can adjust and monitor the distance between the vessels. They exemplify how the UIs can co-exist in the oceanscape and on floating panels with more detailed information inside the ship bridge, such as a screen replacement.

#### 4.1.3 Exploring interaction gestures using VRROS as an underlay

The project assignments emphasized the exploration of interaction mechanisms in sequences. Many student groups used the VRROS as an underlay to contextualize the whole sequence they were working with and thereby managed to convey highly realistic user experiences well suited for plenum discussions (Fig. 5).

To illustrate this, we will describe an example from the second project focusing on ROIs in scenario 2. The group explored how AR interfaces display how ice maps could be designed and various ways the user could interact with the maps to place them correctly, zoom in and out, hide, show and highlight ROIs (Fig. 5). In the project presentation, the group showed how they had conducted their exploration of

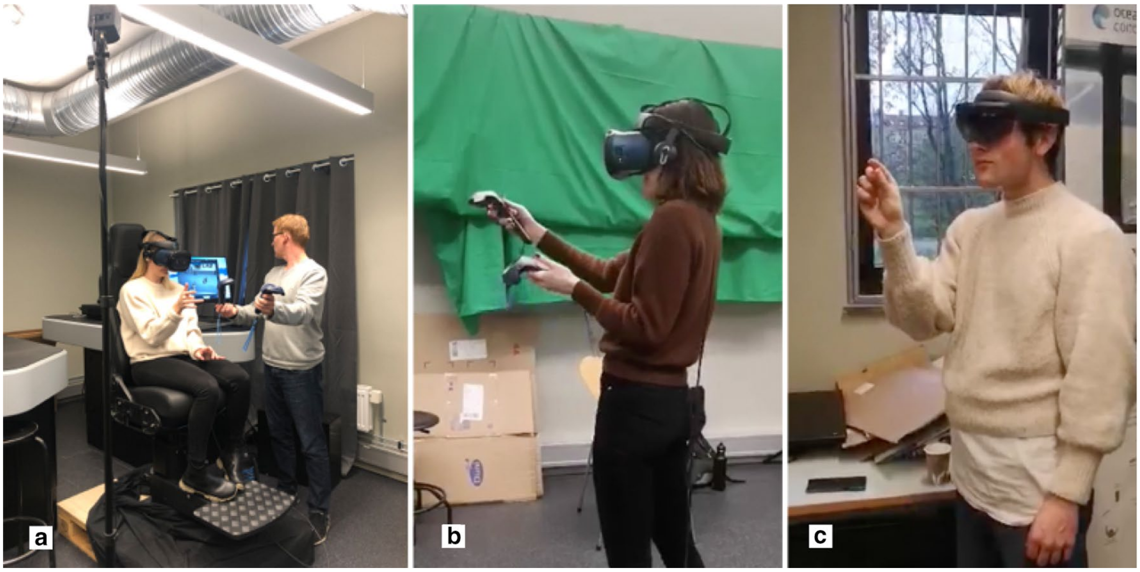



**Fig. 3** Students familiarizing themselves with the use context and testing AR and VR equipment. In **a**, a student sits in the VR simulator with a VR headset on. The simulator was built with an original ship's bridge chair and console tables for flexible setups to test equipment. **b** shows a student testing the VR headset with handle tools that allow the user to interact with the scene by teleporting from one place to another, or pointing or selecting, for example. **c** shows a student exploring the use and interaction possibilities of the AR headset Microsoft HoloLens 1 (Zeller et al. 2019) by testing gestures


**Fig. 4** Screenshots from a video in a student presentation. **a** demonstrates a concept for how navigators can set and monitor the opacity of risk zones in AR using gestures. **b** illustrates the perspective of the navigator, who can monitor the dynamic risk zones in AR projected onto the convoy behind the ship alongside an information panel in the top right corner of this view

finding useful interaction possibilities using the green screen to record various gestures and further combining these with recordings from the VRROS and graphics. Their final concept communicates a navigator applying the graphical ice map to match the outside surroundings, adjusting and rotating the map, and picking up map elements from a screen to further process in AR.

#### 4.1.4 Testing multimodal and distributed interactions with video prototypes

In the project assignments, we encouraged the students to test various interaction modalities on the same problem to understand how interactions need to be designed and distributed across all interfaces to be adaptable to the user situation.

To illustrate this, we will describe an example from the third project focusing on risk proximity in scenario 3 (Fig. 6). The group used the VRROS to video prototype a detailed interaction concept in a selected sequence of the VRROS where the icebreaker vessel is approaching another vessel stuck in ice to rescue it. The group explored several different input and output modalities, such as voice control, gestures, gaze, and command, and finally, by connecting a portable controller for the same interaction functions. Using recordings from the VRROS as an underlay on which to design, the students managed to convey user experiences with a quality and realism that made it possible to evaluate

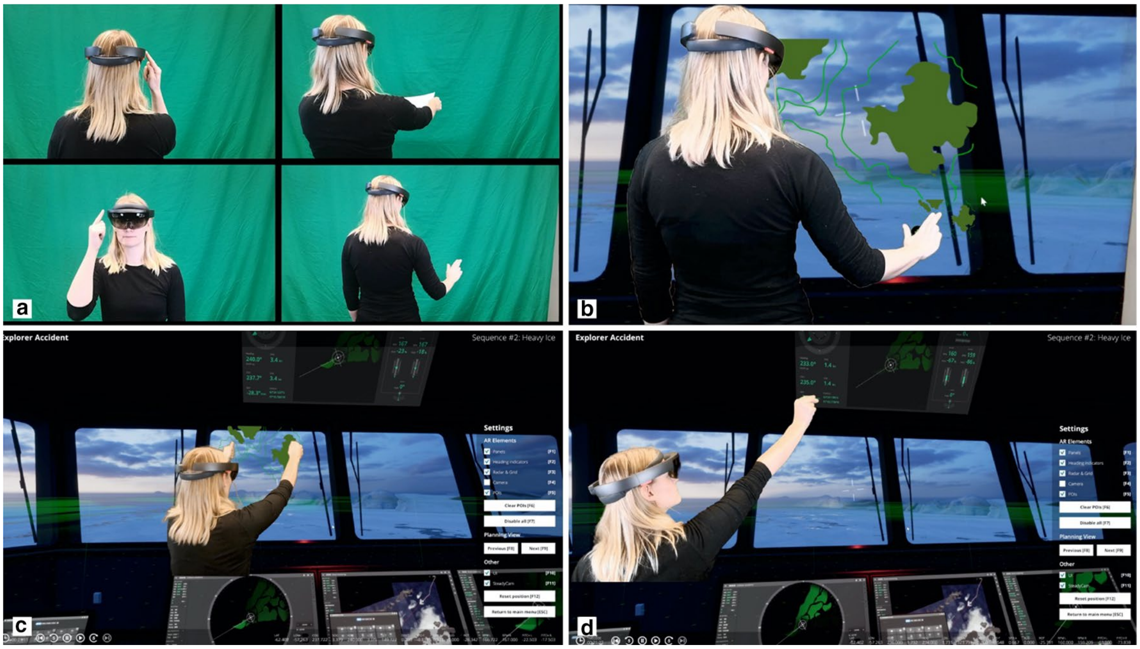



**Fig. 5** A student group's testing of different forms of gestures for interacting with an AR map. **a** shows the use of greenscreen when filming gestures performed by one of the students. The greenscreen makes it easier to further process the recorded material. The recorded gestures were merged with recordings from the VRROS, alongside the graphical dynamic sketches. **b** shows the student applying the graphical map to match the outside surroundings; **c** shows the student adjusting the size and rotation of the map. **d** shows the student picking up map elements from a screen to further process in AR through hand gestures

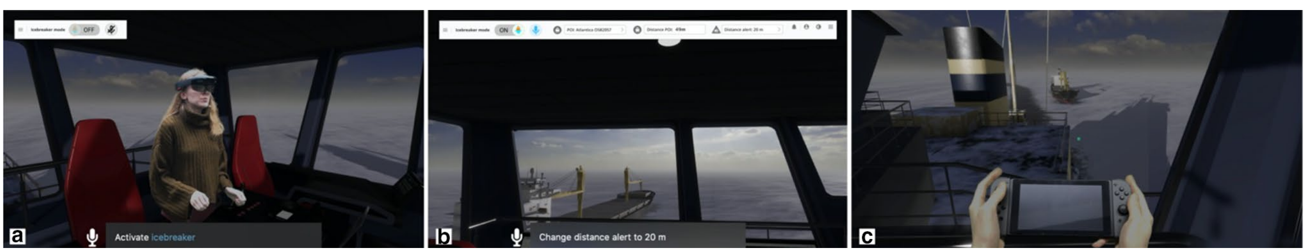



**Fig. 6** Screenshots from a student group's video prototypes of three different ways of solving the same problem using different input and output mechanisms. **a** shows voice controls and gestures. **b** shows gaze and command jointly with graphics. **c** shows interaction with an AR headset and a portable tangible controller

the coherence and consistence of their design proposals across the modalities. They also achieved a greater sense of the situation themselves by playing out the proposals inside the VRROS.

#### 4.1.5 Summary of the students' use of VRROS

Overall, we saw that the students could work creatively with VRROS without having any knowledge of the game engine itself. The students seemed intrigued by and engaged in visiting the virtual ship's bridge to become familiar with the context. Further, some of the groups developed techniques for exploring and implementing design ideas in video recordings from the VRROS in efficient and compelling ways that allowed for fruitful discussions about their design proposals at a satisfactory level of detail. Conversely, the students who did not leverage VRROS in their prototyping seemed to struggle with conveying several aspects of their proposals because they had not worked within dimensions of space and time.

### 4.2 Questionnaire responses

We developed a questionnaire to understand how the students experienced the use of VRROS. In this section, we summarize the students' responses to each of the questions in the questionnaire.

#### 4.2.1 Did you accomplish what you expected (how/why not)?

The students had somewhat diverging expectations for the course, from few expectations to high expectations. Ten students achieved what they expected or more, three students were unsure what they expected or if they accomplished what they expected, and two students stated that they did not expect anything due to reduced access and competence in using the VR equipment.

#### 4.2.2 How did you approach working with a complex user context?

All students were unfamiliar with both the ship's bridges and AR technology. Thirteen students sought additional research to learn about the user context. Although several of them tested the VRROS in the beginning, three students answered that they used the VRROS actively to gain insight into the situation. Two students did not answer this question.

#### 4.2.3 How did you use the VRROS to understand the complex user context?

Seven students who used VRROS found the observation and analysis of the scenarios through the VR simulator useful, especially since the context, the operations, and the domain in general were unfamiliar to them. Two students did not test the VRROS due to voluntary COVID-19 isolation/quarantine. Six students did not answer this question.

#### 4.2.4 How valuable and how useful was the access to the context through the VRROS?

Six students found VRROS valuable and useful. Some of them described how the VRROS contributed to their "mental images" of what they were designing for, which was useful in several parts of the design process conducted outside the simulator, spanning sketching to doing additional research. In addition, they mentioned that the VR simulation helped them understand the scenarios and the context of the situation—the time of day, weather, and light conditions—and what was happening inside and outside the ship. Further, they found the VRROS useful for prototyping "as a background and to test different placements of our user interfaces and our interaction concepts." Eight students did not explicitly answer this question.

#### 4.2.5 How did you approach working with a new technology (if you worked with AR/VR)?

All students tested other prototyping techniques to convey the user experiences they aimed to design, such as through software programs, such as Figma, After Effects, Photoshop, etc., and twelve students described learning new forms for prototyping through this. Eight of the students said that they found it exciting to test the VR and AR equipment and that they had a good impression of how the technology worked. Two students said their approach of using the VR and AR equipment gave them a good understanding of designing for the technology. On student did not answer this question.

#### 4.2.6 How did you relate to working within the time constraints imposed on developing each project?

Four students saw the time constraints as positive. Three students described the time constraint as a challenge. Four students described a steep learning curve and a greater feeling of mastery and satisfaction toward the end of the module. One student found the short-time constraint less comfortable than longer projects. Six students did not answer this question.

#### 4.2.7 How did the COVID-19 measures affect your work?

All students answered that COVID-19 affected their work. Three students answered that they handled the measures well. Ten students answered that difficulties in sharing, discussing, and agreeing on ideas without being physically in the same room were experienced as challenging. Two students did not answer this question.

#### 4.2.8 Summary of the questionnaire

The answers to the questionnaire emphasized that the COVID-19 measures affected the students' ability to do field research and their experience of being free to meet physically and to use the facilities they were actually allowed to use, such as the VR lab and the classroom. This resulted in a split student group, where one part of the students exploited the possibilities of using the VRROS and met physically to engage in teamwork, while the other part worked mostly from their homes, which reduced their ability to cooperate and develop refined prototypes.

## 5 Discussion

### 5.1 VRROS as a substitute

Overall, we suggest that VRROS offers students the potential to access and work with hard-to-reach contexts, such as ships' bridges, in an educational setting where time and organizational constraints often limit real fieldwork. Their use can be unlimited and effortless, and they can be revisited as often as the students are desiring. Regarding the special situation created by the COVID-19 measures placing restrictions on all access to real fieldwork, this proved to be highly important and was even advantageous when compared to the demands of real maritime fieldwork and the associated time, effort, and cost concerns.

The limitations of VRROS compared to real fieldwork are obviously its lack of reality, meaning its lack of real users and all their associated ethnographic aspects, such as culture, language, behavior, etc., that form the basis of what fieldwork actually is. Further limitations are the VRROS requiring a significant amount of time and competence to build a lifelike 3D environment that is realistic enough to be used. However, when VRROS are already developed, the threshold for reusing them for multiple purposes is low. Furthermore, there are a few reasons to develop new scenarios for each semester since the students' means of solving the assignment problems will be unique to each cohort.

### 5.2 Virtual fieldwork

The application of learning concepts in fieldwork is important for designers in both student and professional situations. To answer the RQ of *How can aspects of design-driven fieldwork be substituted with VRROS used in a VR simulator?* we used Anderson's revision (Anderson et al. 2001) of Bloom's levels of cognitive behavior (Bloom 1956) to compare aspects within the different learning concepts. The table lists the learning concepts in the left column, the most prominent aspects within each learning concept facilitated through design-driven virtual fieldwork in the middle column and design-driven field research (Lurås and Nordby 2014) in the right column. More aspects can be added and elaborated. Although some aspects may overlap between both methods, such as the possible range of fidelity variations in the design prototyping, the table intend to display the most expedient qualities and possibilities for learning in each concept.

### 5.3 The VRROS potential

Although virtual fieldwork implemented through VRROS cannot replace the interpersonal aspects of conducting real field research, this method should not be considered a deficient substitute for real fieldwork. During the module, we discovered that the students' use of VRROS' capabilities for manipulation were key for both their understanding of the situation and for prototyping. The VRROSs allowed the students to manipulate some parameters that were not possible in the real world, which are as follows:

- Time: VRROS allows students to oscillate in time as they like. They can freeze time and move slower or faster in time.
- Conditions: VRROS allow designers to change, adjust, and modify certain conditions.
- Situations: VRROS can allow designers to manipulate the situation and the course of action.

All the parameters that can be cross-manipulated result in different possible contextual states. By dwelling on and repeating situations, to modify the situation underlay for testing and to work under various conditions—both separately and cross-manipulated—the students were allowed to work in detail, at their own pace and under controlled circumstances. This strongly opposes the often more chaotic experience of real fieldwork, where conditions and situations are rapidly changing and where the student or researcher must seize opportunities rather than create them.

Our VRROS also offered interesting possibilities for low-threshold but still relatively high-fidelity prototyping. The equipment has a fairly easy setup and the students were able to work independently without further support after a general introduction. Some students spent much time on using the VR- equipment in order to be in the virtual world, while others were content with fetching recordings from the VRROS which they then worked further with in more conventional ways. In an educational setting, it is challenging to teach students about advanced technology design within short-time frames while still facilitating the creation of realistic prototypes. We argue that the quality of realism in prototypes is highly important for the students' understanding of the technology's possibilities and limitations as a design material. Therefore, we propose that the prototyping techniques developed in this module using VRROS in a VR lab are imperative and should be further examined. We would also like to emphasize the potential for implementing virtual fieldwork while undertaking preparatory work before fieldwork trips and to further process design work after fieldwork trips.

In previous research on use of field studies supporting design for safety critical workplaces we found that there was a risk for bias on interpreting the field data due to the designers limited exposure to field context (Lurås and Nordby 2014). We identified three common biases. We do not have the data yet to extrapolate similar biases in use of VRROS in design. However, based on our experience from field studies for design it is likely that there will be biases for interpreting the virtual scenarios in design that needs to be described and compensated for in design processes in further work.

### 5.4 Discussion summary

To summarize and reflect on our research question, we suggest that VRROS can substitute for the following aspects of design-driven fieldwork:

- Observing and analyzing the user context.
- Becoming acquainted with the scenarios regarding operation, time, and space.
- Understanding certain aspects of the situations, such as weather and light conditions
- Understanding what is happening inside and outside the ship from different perspectives
- Collecting background material (videos, images) for prototyping and testing.
- Understanding the design for AR technology on ships' bridges by prototyping realistic mock-ups.
- Working physically and virtually, together with a collective understanding and exploration of the context for which they were designed.

Based on the results, we propose that VRROS offers promising potential to function as a substitute for certain aspects of design-driven field research, such as familiarization and design reflection for prototyping. It is also likely that VRROS can supplement and support actual fieldwork. Although ethnography is excluded, prototyping and several forms of testing can be conducted. Also, aspects of reflection and familiarization, excluding the interrelated aspects of ethnography, can be supported. In our educational case study, VRROS worked as a useful substitute for canceled fieldwork due to the COVID-19 measures implemented. In a learning process with a short-time frame and a context that is difficult to access, we suggest that a VR simulator can actually work as a suitable substitute. Particularly during times of strict COVID-19 measures that limit the movement of people and the accessibility of contexts to a high degree, pragmatic solutions need to be considered good enough, given the circumstances.

## 6 Conclusion

In this article, we described VRROS utilization in a VR lab as a substitute for real fieldwork in the teaching of a master's module on multimodal and distributed technology for ships' bridges. We used two samples: the students' production data and a student questionnaire to answer the RQ: *How can aspects of design-driven fieldwork be substituted with VRROS used in a VR simulator?* Our results showed that VRROS can replace some aspects of the real-world fieldwork. Although important aspects, such as ethnography, cannot be included, the VRROS offers some promising advantages for being far more accessible, faster, and cheaper; they are also time-saving and easy to revisit whenever the designer desires. In addition, VRROS offers students more control in their ability to manipulate the premise of and conditions for testing (which real fieldwork does not), and VRROS enables the students to produce low-threshold, high-fidelity prototypes based on VR recordings when exploring the design possibilities for ships' bridges.

**Acknowledgements** We extend our thanks to the SEDNA team for developing the VRROS and to the OICL team for contributing field research insight and input on transforming our research into an educational module.

**Author contributions** SF devised the project and took the lead in writing the manuscript. KN supervised the project, the writing and contributed to the interpretation of the results. Both authors provided critical feedback and helped shape the research, analysis, and manuscript.

**Funding** The research presented in this article was funded by the EU project SEDNA. This project received funding from the European Union's Horizon 2020 programs for research and innovation under Grant Agreement No. 723526.

**Availability of data and material** The data supporting the findings of this study are available upon request from the corresponding author, SF.

## Declarations

**Conflict of interest** The authors have no conflicts of interest or other competing interest to declare. Both authors have seen and agree on all the details of the manuscript. We confirm that there is no financial or relational interest relevant to the journal *Virtual Reality*. The manuscript has not been submitted to or published in any other journal or publisher.

**Code availability** Not applicable.

**Ethics approval** All procedures performed in studies involving human participants followed the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The project reports to the Norwegian Center for Research Data.

**Consent to participate** Informed consent was obtained from all individual participants included in the study.

**Consent for publication** Informed consent was obtained from all individual participants included in the study.

## References

Adobe (2021) Adobe after effects. https://www.adobe.com/products/aftereffects.html Accessed 22 February 2021

Anderson, LW, Krathwohl, DR, Airasian, PW, Cruikshank, KA, Richard, M, PR, P, Raths, J, MC, W (2001) *A taxonomy for learning, teaching, and assessing:* A revision of bloom's taxonomy of educational objectives (1st). Longman.

Bloom, BS. (1956) Taxonomy of educational objectives: The classification of educational goals—Handbook I: Cognitive domain. David McKay Company, Inc.

Dolphin G, Dutchak A, Karchewski B, Cooper J (2019) Virtual field experiences in introductory geology: addressing a capacity problem, but finding a pedagogical one. J Geosci Edu 67(2):114–130. https://doi.org/10.1080/10899995.2018.1547034

Frydenberg S, Norby K, Eikenes JO (2018) Exploring designs of augmented reality systems for ship bridges in arctic waters. Rina – International conference on human factors, London, UK

Frydenberg S, Aylward K, Nordby K, Eikenes JO (2021) Development of an augmented reality concept for icebreaker assistance and convoy operations. J Mar Sci Eng 9(9):996. https://doi.org/10.3390/jmse9090996

Getchell K, Miller A, Nicoll JR, Sweetman R, Allison C (2010) Games methodologies and immersive environments for virtual fieldwork. IEEE Trans Learn Technol 3(4):281–293. https://doi.org/10.1109/TLT.2010.25

Gonzaga, L, RobertoVeronez, M, Lanzer Kannenberg, G, Nunes Alves, D, Lessio Cazarin, C, Gomes Santana, L, Luca de Fraga, J, Inocencio, LC, Vieira de Souza, L, Marson, F, Bordin, F, Tognoli, FM W (2018) Immersive virtual fieldwork: advances for the petroleum industry. In: 2018 IEEE conference on virtual reality and 3D user interfaces (VR), pp. 561–562

Granshaw F D, Duggan-Haas D (2012) Virtual fieldwork in geoscience teacher education: issues, techniques, and models. Geological society of America special papers, 492(Special Paper of the Geological Society of America), pp. 285–303

Gushima K, Nakajima T (2021) Virtual fieldwork: Designing augmented reality applications using virtual reality worlds. In: Chen JYC, Fragomeni G (eds) Virtual, augmented and mixed reality. Springer, Cham, pp 417–430

Lurås S, Nordby K (2014) Field studies informing ship's bridge design at the ocean industries concept lab. In: international conference on human factors in ship design operation, London, UK

Lurås S, Nordby K (2015) Shaping designers' sea sense: a guide for design-driven field research at sea. In: international conference on marine design 2015, London, UK, https://aho.brage.unit.no/aho-xmlui/handle/11250/2359373

Lurås S, Mainsah H (2013) Reaching hard-to-reach users using online media to get a glimpse of work in marine contexts. Interactions 20(6):32–35. https://doi.org/10.1145/2530539

Lurås S (2016) Systemic design in complex contexts: an enquiry through designing a ship's bridge. Dissertation, Oslo school of architecture and design. https://aho.brage.unit.no/aho-xmlui/handle/11250/2380135

Mäkelä, V, Rivu, R, Alsherif, S, Khamis, M, Xiao, C, Borchert, L, Schmidt, A, Alt, F (2020, April 30) Virtual field studies: Conducting studies on public displays in virtual reality. In: conference: 2020 ACM CHI conference on human factors in computing systems (CHI '20), Honolulu, Hawaii, USA

Mejias A (2017) Virtual fieldwork: a review of the internet: understanding qualitative research. Qual Rep 22(11):3011–3013

Microsoft hololens. Mixed reality technology for business. Available online. https://www.microsoft.com/en-us/hololens (accessed on 21 June 2021)

Minocha, S, Tilling, S, Tudor, A-D (2018, April 25) Role of virtual reality in geography and science fieldwork education. Knowledge exchange seminar series, learning from new technology, Belfast. https://kess.org.uk/2018/05/02/prof-shailey-minocha-dr-ana-despina-tudor-ou-role-virtual-reality-geography-science-fieldwork-education/

Mirauda D, Capece N, Erra U (2019) StreamflowVL: a virtual fieldwork laboratory that supports traditional hydraulics engineering learning. Appl Sci 9(22):4972. https://doi.org/10.3390/app9224972

Mkono M (2012) Netnographic tourist research: the internet as a virtual fieldwork site. Tour Anal 17(4):553–555. https://doi.org/10.3727/108354212X13473157390966

Nordby K, Frydenberg, S, Fauske J (2018) Demonstrating a maritime design system for realising consistent design of multi-vendor ship's bridges. In: human factors conference 2018, London, UK

Nordby K, Gernez E, Mallam S (2019) OpenBridge: designing for consistency across user interfaces in multi-vendor ship bridges. In: ERGOSHIP 2019 conference, Haugesund, Norway

Nordby, K, Etienne G, Frydenberg S, Eikenes JO (2020) Augmenting OpenBridge: An open user interface architecture for augmented reality applications on ship bridges. In: 19th conference on computer applications and information technology in the maritime industries (COMPIT '20), Online/virtual due to COVID-19

NVIDIA (2021) Product: GeForce RTX 3090 Graphics Card. https://www.nvidia.com/en-gb/geforce/graphics-cards/30-series/rtx-3090/. Accessed 22 February 2021

Rekittke J, Pedersen K, Andrews M (2021) Remote wayfaring and virtual fieldwork. J Dig Landscape Archit 6:462–475. https://doi.org/10.14627/537705041

Robins RW, Fraley RC, Krueger RF (2009) Handbook of research methods in personality psychology. Guilford Press, New York

Schön D (1984) The reflective practitioner: how professionals think in action. Basic Books, New York

SEDNA-project.eu (2017) SEDNA. https://sedna-project.eu/ Accessed 22 February 2021

Seifan M, Dada D, Berenjian A (2019) The effect of virtual field trip as an introductory tool for an engineering real field trip. Educ Chem Eng 27:6–11. https://doi.org/10.1016/j.ece.2018.11.005

Tidwell J, Brewer C, Valencia A (2020) Designing interfaces, 3rd edn. O'Reilly media Inc, USA

Unity (2020) 3D software for architecture, engineering SX construction. https://unity.com/solutions/architecture-engineering-construction Accessed 22 February 2021

Zeller M, Miller E, Paniagua S (2019) HoloLens (1st gen) hardware [Documentation]. https://docs.microsoft.com/en-us/hololens/hololens1-hardware Accessed 22 February 2021

# 1 ERRATA

Doctoral candidate: Synne Frydenberg

Thesis title: Cultivating Serendipity in Design Complexity

| Page / line / figure / reference | Original | Correction |
|---|---|---|
| iii /20 | The Context of the **p**roject | The Context of the **P**roject |
| iii /25 | **SA** in High-Risk Environments… | **Situation Awareness** in High-Risk Environments… |
| vi/16 | **RESEARCH** Transferability | **Research** Transferability |
| vi/18 | …and Closing **r**emarks | …and Closing **R**emarks |
| vii/12 | …to contextuali**z**e design… | …to contextuali**s**e design… |
| vii/23 | …of design **precedence**. | …of design **precedents**. |
| vii/24 | …is conceptuali**z**ed through… | …is conceptuali**s**ed through… |
| vii/32 | …it conceptuali**z**es serendipity… | …it conceptuali**s**es serendipity… |
| vii/36 | …design **precedence** and… | …design **precedents** and… |
| viii/10 | …also contextuali**z**e the… | …also contextuali**s**e the… |
| xv/17 | …a ship **where the where the** ship's… | …a ship **where the** ship's… |
| 1/9 | …a **design** experiences… | …a **designer** experiences… |
| 1/ 32,33 | However, designing with novel interaction materials—like AR technologies on ship bridges **(Guo et al., 2022)**—lacks established design precedents, guidelines, or analytical frameworks. | However, designing with novel interaction materials—like AR technologies on ship bridges—lacks established design precedents, guidelines, or analytical frameworks **(Guo et al., 2022)**. |
| 2/ 26 | …practice in **interaction** design… | …practice in **AR** design… |
| 3/ Figure 1 caption | The **V**irtual **R**eality-**R**econstructed **O**peration **S**cenarios… | The **v**irtual **r**eality-**r**econstructed **o**peration **s**cenarios… |
| 6/35 | …advanced operation to… | …advanced operation**s** to… |
| 7/27 | …and **precedence**, such… | …and **precedents**, such… |
| 8/29,30 | …the (OB) design system… | …the **OpenBridge** (OB) design system… |

| | | |
|---|---|---|
| 9/33 | …presenting **an** case study… | …presenting **a** case study… |
| 10/3 | …in the lab, using virtual reality–reconstructed operation scenarios (VRROS). VRROS… | in the lab. |
| 10/30 | …describing **an** case study… | …describing **a** case study… |
| 13/12 | …used in this **study**. | …used in this **thesis**. |
| 15/13 | …challenges in fragmented ship bridges where… | …challenges in fragmented ship bridge **consoles** where… |
| 16/27 | **SA** in High-Risk… | **Situation Awareness** in High-Risk… |
| 16/36 | …and **SA** level (Sharma et al., 2019). | …and **situation awareness (SA)** level (Sharma et al., 2019). |
| 18/16 | …tradition of **HCI** differ from… | …tradition of **Human-Computer Interaction (HCI)** differ from… |
| 18/19 | …to understand **UX**,… | …to understand **User Experience (UX)**,… |
| 18/20,21,22 | Thus, for this thesis, SA was a guiding concern for developing design heuristics (Schønheyder, 2019) rather than a measure for outcomes. | In this thesis, SA served as a foundational concern guiding the development of design heuristics, rather than as a measure for evaluating outcomes (as discussed by Schønheyder, 2019) |
| 21/9 | …bridge systems (Hareide & Ostnes, 2017b. | …bridge systems (Hareide & Ostnes, 2017b**)**. |
| 22/29 | …is visualised **in situ** (Bressa et al., 2022). | …is visualised ***in situ*** (Bressa et al., 2022). |
| 24/22 | …captivating **user experience (UX)** in… | …captivating **UX** in… |
| 29/31 | …where **complexus** (derived from **complecti**) combines **com** and **plectari**, signifying 'ply' or 'braid' (Cooke-Davies et al., 2007, p. 51). | …where ***complexus*** (derived from ***complecti***) combines ***com*** and ***plectari***, signifying 'ply' or 'braid' (Cooke-Davies et al., 2007, p. 51). |
| 33/ Figure 6 | Close to **certianty**<br><br>Far from **certianty** | Close to **certainty**<br><br>Far from **certainty** |
| 33/ Figure 6 | …and **odealogical** control… | …and **ideological** control… |
| 42/9 | …especially **withing** the context… | …especially **within** the context… |
| 43/36,37 | …to as 'slippery concept' (Makri & Blandford, 2012). | …to as **a** 'slippery concept' (Makri & Blandford, 2012). |
| 51/18 | …apparent there… | …apparent **that** there… |

| | | |
|---|---|---|
| 51/30 | In this chapter, I established… | In this chapter, I **have** established… |
| 51/35 | …design **precedence** and… | …design **precedents** and… |
| 55/4 | …research by and **for** design. | …research **by / into** design. |
| 71/ Figure 15 | Research **for** Design | Research **into** Design |
| 78/1 | …design **precedence** and… | …design **precedents** and… |
| 78/3 | …design **precedence** and… | …design **precedents** and… |
| 83/38 | …of design **precedence** and… | …of design **precedents** and… |
| 87/Figure 17 | …Exemplified with Point of Interest Widget in Aft bridge view in the 'Icebreaker Assistance' App from… | …**e**xemplified with **p**oint of **i**nterest **w**idget in **a**ft bridge view in the 'Icebreaker Assistance' **a**pp from… |
| 88/21 | …design **precedence** generally… | …design **precedents** generally… |
| 149/ Figure 39 | Co-design, Co-evolution | Codesign, coevolution |
| 92/30 | …and design **precedence** in… | …and design **precedents** in… |
| 163/ 9 | …of design **precedence**,… | …of design **precedents**,… |
| 168/20 | …design **precedence** for… | …design **precedents** for… |

# Synne Frydenberg

## CULTIVATING SERENDIPITY IN DESIGN COMPLEXITY

Designing augmented reality (AR) systems for ship bridges poses intricate challenges for interaction designers due to the unique complexities involved in working with this novel interaction material in a dynamic and unpredictable environment. The absence of established design precedents and guidelines for AR systems exacerbates these challenges, thereby reflecting a broader need for guidance in navigating the rapidly evolving digital landscape of interaction design.

This thesis aims to explore and identify how design complexity can be effectively managed by introducing serendipity into the design process. Employing a research-by-design and research-into-design approach, this study utilises embedded case studies to contextualise design complexity within the specific context of designing AR technology for ship bridges. It develops conceptual frameworks, practical methods, tools, and approaches to illustrate how serendipity mechanisms and qualities can be cultivated and pragmatically integrated into the design process.

*Synne Frydenberg is a design researcher, interaction designer, and lecturer. Holding an Industrial Design master's degree from AHO (2011), her academic journey included foundational studies at The Royal Danish Academy and an exchange at the Berlin University of the Arts. With over 13 years of experience as an interaction designer, she has spent the last six years specialising in complex design for safety-critical workplaces. Currently, she serves as a design researcher in the Ocean Industries Concept Lab at AHO. Her research contributions have been integral to the EU-project 'Safe Maritime Operations under Extreme Conditions: The Arctic Case (SEDNA)', as well as the research projects OpenBridge and OpenAR.*

ISSN: 2703-691X
ISBN: 978-82-547-0370-0

PhD thesis 126