THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Distributed Participatory Design in Multidisciplinary Engineering Projects:

Investigating a Sustainable Approach for Ship Design & Construction

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About the Cover Image:

The cover image used for this thesis is *The S.S. Imogene with Crew* by David Blackwood, CM. David is a Canadian artist from Wesleyville, Newfoundland; the community of my mother's family. His art commonly portrays Newfoundland outport life and maritime themes which I have been privileged to have had part of my life since I was a young child. David has graciously given permission to use an image of his original watercolour for the cover of this thesis, which holds a particularly special meaning to me. *The S.S. Imogene with Crew* depicts the general arrangement of a steamship my great-grandfather, Captain Sidney Hill worked on during the early twentieth century. I never knew my great-grandfather, but his daughter played a pivotal role in my upbringing. I have always associated David Blackwood and his art with my grandmother. His work has subtly permeated my life, inspiring curiosity, teaching me about my family, Newfoundland and maritime history, and was an early foundation for my interest in seafaring and maritime safety. I chose *The S.S. Imogene with Crew* as the cover image for my thesis because it connects and represents many aspects of who I am. It pays homage not only to my family and the island where I grew up, but also to my Doctoral research and the utilization of general arrangement drawings as a tool to facilitate participatory design processes in naval architecture, and ultimately the development of safer, more productive work environments for people at sea.

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For Martha Andrews,

thank you for teaching me the importance of education and curiosity

Abstract

Naval architecture design procedures focus primarily on the technical aspects of engineering specifications, mission requirements and overall survivability of ships and marine structures. In contrast, often little attention or importance is placed on the operational demands of onboard crew and the detailed design characteristics of a ship's work environment. However, the design and layout of a ship's work environment influences how crew execute their tasks. Ship designs not optimized for crew and their work demands can contribute to decreased safety and efficiency, while increasing the physical demands of onboard operations. Inadequate design is a common causal factor of maritime accidents, and thus, should be addressed and mitigated during conceptual design development.

The aim of this thesis is to investigate and identify strategies that facilitate the implementation of user-centred design solutions during new ship development, and ultimately optimize the onboard work environment for crew. This thesis has a design-centred scope which explores and develops pragmatic methods and tools to improve knowledge mobilization and participatory design processes between multidisciplinary, geographically-distributed stakeholders involved in new ship development.

This research confirms that general arrangement drawings are an effective, pragmatic participatory platform that designers, users and ergonomists can utilize as a communication tool for early evaluation and design input. Visual representations of a ship's structure and work environment facilitates storytelling and contextualizes highly specialized, tacit crew knowledge and experiences. This allows for design decision-making to be openly discussed, visualized and optimized through tangible, highly iterative processes and directly validated by subject-matter experts. Results from this research were used to develop the software prototype, *E-SET*, which uses digital general arrangement drawings and ship renderings as a participatory platform for crowdsourced evaluation and input. The prototype's usability was tested by naval architecture graduate students, while the adoption of new technology and ergonomics applications in ship design projects was further investigated.

Ergonomics, as a discipline, must demonstrate tangible added value to traditional engineering design processes in order to motivate industry stakeholder buy-in. Ergonomics applications will be more likely utilized by naval architects and applied within the shipping industry if the tools and methodologies developed are not only usable and convenient, but produce measurable and cost-effective outcomes. However, before ergonomics is to make a meaningful and widespread impact within shipping the attitudes and cultural norms of the industry must evolve as a precondition for knowledge transfer to successfully occur.

Keywords: Maritime; Ergonomics; Built Environment; Knowledge Transfer; Naval Architecture; Industrial Design; User-Centred Design; Technology Acceptance

List of Publications

Appended Articles

Article I:

Mallam, S. C., & Lundh, M. (2016). The Physical Work Environment & End-User Requirements: Investigating Marine Engineering Officers Operational Demands & Ship Design. *Work, 54*(4), 989-1000. DOI: 10.3233/WOR-162365

Article II:

Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2015b). Integrating Human Factors & Ergonomics in Large-Scale Engineering Projects: Investigating a Practical Approach for Ship Design. *International Journal of Industrial Ergonomics, 50,* 62-72. DOI: 10.1016/j.ergon.2015.09.007

Article III:

Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2017b). E-SET: Ergonomic Ship Evaluation Tool. *Manuscript accepted for publication in Ergonomics in Design.*

Article IV:

Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2017a). Evaluating a digital ship design tool prototype: Designers' perceptions of novel ergonomics software. *Applied Ergonomics, 59*(Part A), 19-26. DOI: 10.1016/j.apergo.2016.08.026

Additional Relevant Publications

Peer-Reviewed Conference Proceedings

de Vries, L., Costa, N., Hogström, P., & **Mallam, S.** (2015). Overcoming the challenges of integration of Human-centred Design within the Naval Architecture ship design process. In *Proceedings 19th Triennial Congress of the International Ergonomics Association*, August 9th-14th, 2015, Melbourne, Australia.

Lundh, M., Blomé, M., **Mallam, S.,** & Paraïso, J. (2013). Visualising design problems and solutions of workstations on ships. In V. G. Duffy (Ed.), *Digital Human Modeling and Applications in Health, Safety, Ergonomics, and Risk Management. Human Body Modeling and Ergonomics* (Vol. 8026, pp. 252-260). Berlin, Heidelberg, Germany: Springer-Verlag. DOI: 10.1007/978-3-642-39182-8_30

Lundh, M., **Mallam, S.**, & MacKinnon, S. (2016). A General Arrangements Visualization Approach to Improve Ships' Design and Optimize Operator Performance. In *Proceedings of COMPIT 2016: The 15th International Conference on Computer Applications and Information Technology in the Maritime Industries,* May 9th-11th, 2016, Lecce, Italy.

Lundh, M., **Mallam, S. C.**, Smith, J., Veitch, B., Billard, R., Patterson, A., & MacKinnon, S. N. (2012). Virtual Creative Tool: Next Generation's Simulator. In *Proceedings of Maritime Simulation (MARSIM) 2012: International Marine Simulator Forum*, April 23rd-27th, 2012, Singapore, Republic of Singapore.

Mallam, S. C., & Lundh, M. (2013). Ship Engine Control Room Design: Analysis of Current Human Factors & Ergonomics Regulations & Future Directions. In *Proceedings of the Human Factors & Ergonomics Society 57th Annual Meeting, 57*(1), 521-525. DOI: 10.1177/1541931213571112

Mallam, S. C., & Lundh, M. (2014). Conceptual Ship Design, General Arrangement & Integration of the Human Element: A Proposed Framework for the Engine Department Work Environment. In *Proceedings: 11th International Symposium on Human Factors in Organisational Design and Management & 46th Nordic Ergonomics Society Conference* (Vol. II, pp. 829-834), August 17th-20th, 2014, Copenhagen, Denmark.

Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2016). Supporting Participatory Practices in Ship Design and Construction – Challenges and Opportunities. In *Proceedings of the Human Factors & Ergonomics Society 60th Annual Meeting, 60*(1), 1004-1008. DOI: 10.1177/1541931213601233

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Mallam, S. C. (2015). Development & Delivery of a New Bachelor's Level Course: Methods & Experiences From a Novice. *Abstract presented at Chalmers Conference on Teaching & Learning*, January 14th, 2015, Gothenburg, Sweden.

Mallam, S. C. (2016). Evaluating Students of Disparate Academic Programs and Mixed-Levels in a Post-Secondary Elective Course. *Abstract presented at Chalmers Conference on Teaching & Learning*, January 12th, 2016, Gothenburg, Sweden.

Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2015). Conceptual Design vs. Constructed Reality – Comparing General Arrangement Drawings to the Finalized Working Environment. In *Proceedings 19th Triennial Congress of the International Ergonomics Association*, August 9th-14th, 2015, Melbourne, Australia.

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Peer-Reviewed Book Chapters

Lundh, M., & **Mallam, S.** (2015). Operational Requirements of Shipboard Engineers: Workability and Maintainability. In F. Laffoucrière (Ed.), *Improving Ship Operational Design (2nd ed.)* (pp. 85-90). London, United Kingdom: The Nautical Institute.

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List of Abbreviations & Symbols

CAD	Computer-Aided Design
DOI	Diffusion of Innovation
E	Ergonomics
E-SET	Ergonomic Ship Evaluation Tool
GA	General Arrangement
GUI	Graphical User Interface
HF	Human Factors
IEA	International Ergonomics Association
ILO	The International Labour Organization
IMO	International Maritime Organization
ISM	The International Safety Management Code
ISO	International Organization for Standardization
m	Meters
min	Minutes
MS	Motor Ship
PSSUQ	Post-Study System Usability Questionnaire
RMS	Royal Mail Ship/Steamer
RO-RO	Roll-On Roll-Off
s	Seconds
SD	Standard Deviation
SME	Subject-Matter Expert
SOLAS	The International Convention for the Safety of Life at Sea
STCW	The International Convention on Standards of Training Certification & Watchkeeping
TAM	Technology Acceptance Model
TEU	Twenty Foot Equivalent Unit
TOE	Technology, Organization and Environment
TPB	Theory of Planned Behavior
TRA	Theory of Reasoned Action
UTAUT	Unified Theory of Acceptance and Use of Technology
2D	Two-Dimensional
3D	Three-Dimensional
$\bar{x}$	Sample Mean

Chapter 1

Introduction

Commerce through ocean-bound trade has a history thousands of years old (Paine, 2013). Maritime shipping (henceforth referred to as "shipping") has had profound economic and cultural impacts on human civilization, expedited globalization in the post-Columbus era and continues to have a vital impact on our society today (Mann, 2011). It is both historically and contemporarily one of the most global and economically important industries in the world (Progoulaki & Roe, 2011). Shipping remains the safest, cheapest and most environmentally friendly form of transporting goods over long distances (Ashmawy, 2012). However, industries where humans engage in work on or near water are inherently dangerous. Shipwrecks, disasters and accidents at sea are part of seafaring history and culture, revealing the fundamentally hazardous nature of shipping (Bloor, Thomas & Lane, 2000; Hetherington, Flin & Mearns, 2006; Håvold, 2005).

Shipping has undergone vast transformations. Rapid technological advancements continue to evolve and alter the industry and its operations. One of the fundamental purposes of introducing advanced technologies in shipping has ultimately been to reduce accidents at sea (Allen, 2009). Advancements in naval engineering and operational practices coupled with the international codification of construction and operational rules and regulations throughout the twentieth century (International Maritime Organization [IMO], 2016a) have led to a consistently declining trend of shipping accidents over the past century (Chauvin, Lardjane, Morel, Clostermann & Langard, 2013).

Shipping is a competitive industry (Stopford, 2009) and a major focus is placed on productivity and efficiency of operations in order create an economically sustainable business model (Bhattacharya, 2015). The advancements and proliferation of computerization of onboard operations have become increasingly prevalent and desired by ship-owners due to their contribution to increased efficiency (Grech, Horberry & Koester, 2008). Manning expenses for ship operations of a given charter can range up to ten percent of the total costs (however, these numbers are highly variable and mostly dependent on fluctuating bunker fuel prices) (Rødseth & Burmeister, 2012; Stopford, 2009). Reducing manning levels is one area where shipping companies can straightforwardly cut costs from their budgets (Hummels, 2007) and increasing automation has made it possible to continue to remove onboard crew (Barnett, Stevenson & Lang, 2005; Progoulaki & Roe, 2011).

As technologies have evolved and reduced manning numbers, smaller crew onboard ships have had their task demands altered and have found difficulty managing the complexity of their work (Lundh, Lützhöft, Rydstedt, & Dahlman, 2011; Lundh & Rydstedt, 2016). The design and layout of ship work environments are generally not created to optimize user task demands (Forsell, Hagberg & Nilsson, 2007; Nielsen & Panayides, 2005; Orosa & Oliviera, 2010). Human error is often identified as the main contributor of maritime accidents (Hetherington, Flin & Mearns, 2006; Rumawas, 2016), while inadequate design is responsible for approximately one third of all accidents (Grech, Horberry & Koester, 2008). Graveson

(2002) notes that the influential role of the human element in maritime accidents demands that onboard crew operations and work demands be taken seriously and addressed in ship design.

Ship procurement and the process of ship design and construction involves a variety of multidisciplinary stakeholders, many whom have little awareness about the human element involved in ship operations (Earthy & Sherwood Jones, 2010). The maritime domain lacks an interconnected link between ship design and user needs. A methodological and technological gap exists in current ship design practices for crew, who have valuable operational knowledge and experience to be utilized in ship development (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012). User involvement facilitates improved design decision-making and outcomes that contribute to a range of benefits, including increased system safety and reliability, improved work efficiency and life-cycle cost-savings (Hendrick, 2008).

1.1. Research Background

This thesis is part of a research programme titled "Engine Room Ergonomics and Safety". It was established to contribute to the improvement of working conditions of engine department crew, with a long term goal of providing input for the development of mandatory design and operations-related rules and regulations. In order to achieve these overall objectives, the research program was structured to define the work roles and requirements of the engine crew and develop strategies to implement user-centred design throughout new ship development. The focus was to develop technical and methodological solutions to facilitate the evaluation and optimization of the design and layout of machinery spaces in order to improve the work environment for the crew.

The first publication of the author's Doctoral research program was a collaborative effort which examined the potential applications of virtual platforms and simulation as design and training tools in the shipping domain (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012). Figure 1 outlines the overall scope that the author's Doctoral research program was based on. The author's specific research interests and focus of this thesis is on investigating solutions which can facilitate participatory processes and user involvement during ship design and evaluation phases.

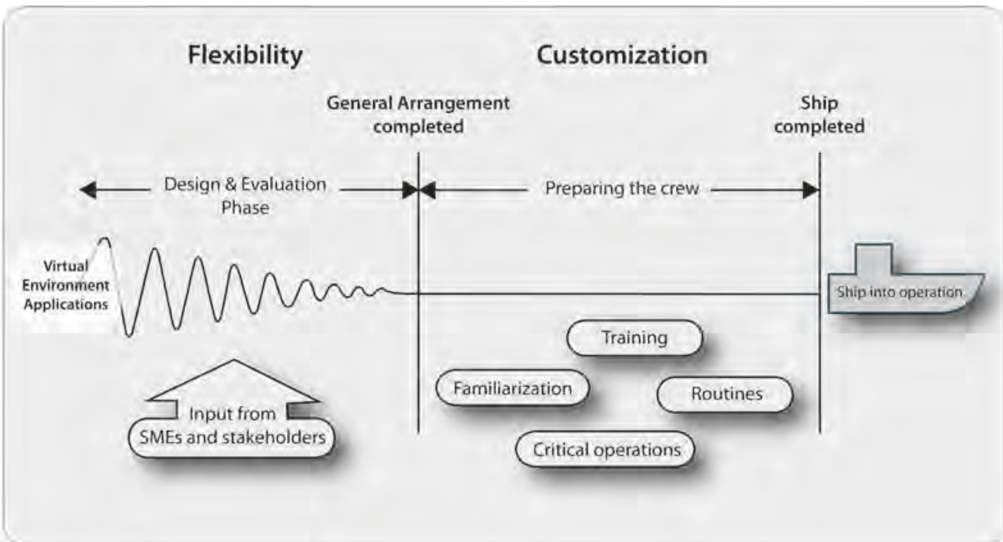

Figure 1. Virtual environment applications: user design & training aids (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012).

The intense work environment and physical requirements demanded of the engine crew made the engine department a logical starting point for ergonomics analysis. The author's research initially focused exclusively on engine crew and the engine department (e.g. Mallam & Lundh, 2013; Mallam & Lundh, 2016; Mallam, Lundh & Smith, 2012). As the scope of work moved more towards developing methods to facilitate participatory approaches to early ship design, the original engine department scope was expanded in order to take a more comprehensive perspective to ship design and operation procedures. As naval architects develop ship structures holistically and iteratively, and no one crewmember or ship's department exists in isolation, the research scope and ergonomics integration strategies were soon expanded to the entire ship.

1.2. Research Scope & Aim

The aim of this thesis is to investigate and identify strategies to utilize during new ship development that facilitate the implementation of user-centred design solutions to ultimately contribute to an improved onboard work environment for crew. The research scope has investigated a participatory approach for improving knowledge mobilization between key stakeholders to facilitate the integration of ergonomics and user knowledge into ship design and construction processes.

The main objective and overall scope of this thesis has been ***to better understand how ergonomics solutions and their implementations can overcome multidisciplinary, geographically-distributed stakeholder networks in large-scale engineering projects.*** This objective is addressed by the following research questions:

1. Are general arrangement (GA) drawings a suitable platform for meaningful ergonomics evaluations and design input throughout ship development?

2. Can GA drawings facilitate participatory design practices between multidisciplinary project stakeholders?

3. How can technology facilitate knowledge mobilization and bridge communication gaps between geographically-distributed project stakeholders, enabling ergonomics and participatory design practices? Furthermore:
    a. What are the desired characteristics and functions of a technical solution aimed to facilitate ergonomics interventions and participatory design practices?
    b. Are there barriers of inclusion for ergonomics and ergonomics-based technologies in ship design and construction?

1.3. Delimitations

1.3.1. Merchant Navy

The research within this thesis, and its appended articles, is focused on the merchant navy. The conclusions drawn from this research are derived from a sample consisting of large merchant ships and their crew. Specifically, the data collections included within this thesis used three different ships: (i) a Roll-On Roll-Off (RO-RO) passenger ferry, (ii) a RO-RO cargo ship and (iii) a chemical bulk carrier. Although the content may be applied across different types of maritime and non-maritime structures and industries it was not the focus of this research.

1.3.2. Design Focused Scope

The data collections implemented, as well as the technology and methodologies developed and presented in this thesis were focused on design processes and select stakeholders. Inspired by the framework proposed by Vink, Imada & Zink (2008), the primary stakeholder groups involved in system analysis and idea generation phases of an ergonomics process are the employees (i.e. seafarers), designers (i.e. naval architecture students) and ergonomists (i.e. the researchers). The research within this thesis focuses on these three groups, and although other stakeholders and variables found in real-world ship design and construction projects are discussed (e.g. economics, project management, etc.), it is not explicitly investigated in these data collections.

1.3.3. Academic Research

The methodologies and technologies developed and tested in this thesis have been from a theoretical perspective within an academic research program. The research was not applied or tested in a real-world ship design and construction project.

1.3.4. Participant Characteristics

Subject-Matter Expert (SME) professional seafarers were all certified and currently employed on the aforementioned types of ships. However, they may have had prior experience on other merchant or non-merchant ships types (i.e. Navy, Coast Guard, pleasure crafts, etc.), which may have influenced their responses.

The participants recruited for the data collection which investigated the usability testing of the digital design tool prototype, *E-SET* (Ergonomic Ship Evaluation Tool), were Naval Architecture and Ocean Engineering graduate students nearing the end of their degree, with little or no real-world industry experience.

1.4. Summary of Publications

This thesis is based on four peer-reviewed journal articles and extended research from the Licentiate thesis publication, Mallam (2014). Each article is found in full within the appendix of this thesis. Steven C. Mallam is the first author and main contributor to each of the appended articles, while co-authors assisted and supervised their development. The four articles are presented in chronological order as they were performed throughout the research program. As the submission, review and publication processes of each journal differs, the official journal publication dates varies slightly from the order in which they were planned and executed.

The four appended articles detail the development of the author’s research scope in an effort to answer the established thesis’s research questions in a logical order. This moves from an initial investigation of how users relate to GA drawings (article I); to an onboard ship study comparing conceptual GA drawings to the realities of a constructed and operational ship (article II); to the rationalization and development of a software prototype to facilitate communication between multidisciplinary stakeholders (article III); to usability testing and technology acceptance of the first digital prototype with naval architecture students (article IV).

Article I

Citation: Mallam, S. C., & Lundh, M. (2016). The Physical Work Environment & End-User Requirements: Investigating Marine Engineering Officers Operational Demands & Ship Design. *Work*, *54*(4), 989-1000. DOI: 10.3233/WOR-162365

Summary: This article investigated the relationship between onboard crew (specifically engine crew) operational task demands and their onboard work environment. Marine engineers participated in semi-structured focus groups to discuss how they viewed themselves within the operational ship system. Research questions revolved around the human element within a ship's operational system, how crew tasks and demands related to different areas of a ship and their connection to physical design and layout. Design choices made in a ship's GA were described to inherently influence how individuals and teams are able to function within the system. Participants detailed logistical relationships between key areas, stressing that the work environment and physical linkages must allow for flexibility of work organization and task execution.

Contribution to Thesis: Investigating the relationship between user tasks and their work environment via ship drawings and general sketching provided initial testing for how GA drawings could be used as a common platform between multidisciplinary stakeholders, and tool to illustrate and evaluate ergonomics issues.

Article II

Citation: Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2015b). Integrating Human Factors & Ergonomics in Large-Scale Engineering Projects: Investigating a Practical Approach for Ship Design. *International Journal of Industrial Ergonomics, 50,* 62-72. DOI: 10.1016/j.ergon.2015.09.007

Summary: This data collection extended the findings of article I investigating the use of a ship's GA drawings as a pragmatic platform for multidisciplinary stakeholder input throughout ship development. An onboard data collection was completed using a cargo ship and its crew as a case study. A comparative analysis between the ship's two-dimensional GA drawings from which the structure was built and the constructed onboard work environment was performed.

Additionally, the engine crew was job-shadowed and interviewed to gain insight into their work demands and movement within the space. Although inaccuracies were found between the conceptual drawings and the constructed reality, GA drawings were found advantageous in mapping and visualizing logistical routing which can be evaluated early in ship development. It was found that crew modified poor designs and layouts of the original construction to improve their work environment.

Contribution to Thesis: This investigation explores the benefits and limitations of two-dimensional (2D) GA ship drawings. It further develops the concept of pairing task and link analyses in order to organize and visually map crew movement patterns for individual work tasks throughout a structure.

Article III

Citation: Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2017b). E-SET: Ergonomic Ship Evaluation Tool. *Manuscript accepted for publication in Ergonomics in Design.*

Summary: Article III outlines the rationale and background for both a pragmatic ergonomics integration strategy specifically customized for ship design, and its influence on development choices of a first-generation software prototype, eventually named *E-SET*. *E-SET* was developed to facilitate participatory design processes and ergonomics integration throughout ship design. *E-SET* is a diagnostic visualization tool and participatory platform which utilizes digital renderings of ship's drawings to quantitatively calculate, map and evaluate physical movement of crew work tasks throughout a ship's structure.

Contribution to Thesis: Based on the findings of articles I and II (as well as several other publications within the research program: e.g. Mallam, Lundh & Smith, 2012; Mallam & Lundh, 2014; Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012; Lundh, Paraïso & Mallam, 2013), *E-SET* was developed to provide a flexible and widely accessible digital platform for geographically-distributed, multidisciplinary stakeholders. This tool uses GA drawings as a common object between all parties, and task and link analyses to document, organize and visualize work tasks and crew movement to facilitate ergonomics evaluation, knowledge transfer and optimization of design solutions throughout ship design.

Article IV

Citation: Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2017a). Evaluating a digital ship design tool prototype: Designers' perceptions of novel ergonomics software. *Applied Ergonomics, 59*(Part A), 19-26. DOI: 10.1016/j.apergo.2016.08.026

Summary: Article IV uses a mixed-methods framework to explore how new ergonomics technology is perceived by naval architecture students. Overall, results found participants perceived the software and its embedded ergonomics tools to benefit their design work, increasing designer empathy and ability to understand the work environment and work demands onboard crew face. However, participant's questioned if ergonomics could be practically and efficiently implemented under real-world project constraints. This reveals underlying social biases and a fundamental lack of understanding in engineering postgraduate students regarding applied ergonomics in naval architecture.

Contribution to Thesis: As the purpose of the author's Doctoral research program was to develop methods and a technical solution to improve crew working conditions during conceptual ship design, the software prototype developed had to be tested and evaluated by those who create ship designs. This test evaluated the first generation of *E-SET* to provide a benchmark for not only the software prototype, but also the perceptions and opinions of naval architecture students towards ergonomics applications in engineering processes and new technology. Additionally, data were used to develop future research and ideas for both *E-SET* and ergonomics applications in ship design and construction.

1.5. Thesis Structure

This thesis consists of eight chapters, as well as an appendix containing the four journal articles that the content of this thesis is structured upon. Chapter 1 presents a general introduction to the maritime industry, as well as the scope and purpose of the work presented within this thesis. Chapter 2 provides an overview of the ergonomics domain, applying ergonomics in practice, and a background to the relevant issues of merchant shipping operations and new ship development. Chapter 3 presents the theoretical framework of this thesis. As design and multidisciplinary project work represent the foundation for this thesis's research questions, this chapter presents the design approaches, knowledge management and technology adoption theories utilized. Chapter 4 provides an overview of the research approach, methods, procedure and data analyses performed in each data collection. Chapter 5 reports selected main findings from the four appended articles, while their implications and a broader discussion of the research, recommendations to stakeholders and future research directions are found in Chapter 6. Chapter 7 summarizes and highlights main conclusions and research contributions of the thesis. Chapter 8 provides a full list of all references used within the thesis text.

Chapter 2

Background & Context

2.1. Defining Ergonomics & The Human Element

The International Ergonomics Association (IEA) (2016) defines ergonomics as:

> *"…the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance."*

"Ergonomics" and "human factors" are both common and often interchangeable nomenclature in contemporary usage (IEA, 2016; International Organization for Standardization [ISO], 2011). There are many differing and overlapping definitions, however, any description of "ergonomics" and/or "human factors" should highlight the need for understanding people and their interactions, and strive to improve and optimize those interactions which can be studied from physical, cognitive and organizational perspectives (IEA, 2016; Wilson, 2000). The nomenclature for describing the field itself varies widely; for example, "ergonomics", "human factors", "human factors and ergonomics" (HF&E, HFE), "human factors/ergonomics" (HF/E), "ergonomics/human factors" (E/HF), "human factors engineering" (also using the acronym HFE), "human engineering" and "human factors and ergonomics engineering" are a sample of terms describing what are arguably similar, if not identical concepts. This seemingly trivial discussion over minor semantics has greater implications for a field without a single, unified and well-recognized name (Dempsey, Wogalter & Hancock, 2000). The interchangeable nomenclature, in particularly, the varying combinations of "ergonomics" and "human factors" has implications for how the field is understood by people working both within the field itself, as well as non-experts and "outsiders".

As the scope of this thesis is focused on the integration of "ergonomics" and/or "human factors" within the maritime context and specifically within engineering and industrial design disciplines, how the field is labelled and perceived is of great interest. The publications appended within this thesis have used a variety of terms in their titles and body of text (predominantly "ergonomics" or "human factors and ergonomics" with abbreviations HF&E and HF/E). Although in each respective publication an attempt has been made to keep the chosen nomenclature consistent, over the span of the research program the author's terminology usage has evolved, reflecting altering perspectives, and is therefore not consistent across this thesis's appended articles.

The research within this thesis is focused on the study of work: the maritime domain, shipping systems and the people within these systems. In order to establish consistent terminology when referring to the scientific discipline itself, "ergonomics" is chosen over all other alternatives. With specific regards to the maritime domain, the term "human element" has been adopted to describe the people and human activities within the entire spectrum of shipping (including all relevant stakeholders to this thesis's scope: e.g. ships' crew, naval architects, shipyards, regulatory bodies, etc.) (IMO, 2016b). Within shipping the term "human element” was first adopted by the IMO to acknowledge the importance of people in maritime safety and environmental protection (IMO, 1997), but is now widely used across the industry and literature relating to maritime issues. Thus, the “human element” is used to describe the people working within the shipping industry, which in the context of this thesis predominantly refers to the onboard crew.

2.1.1. Contemporary Physical Ergonomics Issues

Physical ergonomics in design provides tangible frameworks and understanding of the relationships between humans, technology and the greater environment (Vicente, 2006). The fundamental basis for ergonomics and design grew from the desire to improve safety and increase productivity through understanding and altering physical design. Before ergonomics was formalized as a scientific discipline in the twentieth century its applications were documented throughout history: from matching rudimentary stone tools to users of the Neolithic Age (Meister, 1999); to the Ancient Greeks applying user-centred practices to household tools, construction sites and surgical theatres (Marmaras, Poulakakis & Papakostopoulos, 1999); to Ramazzini’s observations of worker diseases and injuries in the eighteenth century (Franco & Franco, 2001). Initial areas of interest were worker anthropometry, working postures, fatigue, musculoskeletal disorders, work environment and tool design. After World War II computerization and technological advancements rapidly evolved and influenced society that is now dominated by digital technologies and increasingly complex systems.

Technological change has, and continues to alter workplaces through computer-based systems (Woods & Dekker, 2000). New technologies create unintended complexities and alterations to task strategies for users (Ivergård & Hunt, 2009; Knudsen, 2009; Venkatesh, 2000; Woods & Dekker, 2000). Desk and computer-based work is a hallmark of the modern information economy. Work systems have moved away from high levels of physical activity to increasingly sedentary jobs, while the need for manual labour is continually reduced through computerization, automation and robotics (Straker & Mathiassen, 2009). However, musculoskeletal disorders (predominantly the back, neck and upper limbs), cardiovascular diseases, type II diabetes, some cancers and all-cause mortality continue to have large economic implications and are growing in prevalence (Collins & O’Sullivan, 2015; Stamatakis, Chau, Pedisic, Bauman, Macniven, Coombs & Hamer, 2013; Bauman, Ainsworth, Sallis, Hagstromer, Craig, Bull, Pratt, Venugopal, Chau & Sjostrom, 2011; Deyo, 1998; European Agency on Safety and Health at Work, 2010; Robertson, Huang & Larson, 2016; Wilmot, Edwardson, Achana, Davies, Gorely, Gray, Khunti, Yates & Biddle, 2012).

In shipping, onboard work has also evolved towards computer-based operations and centralized control areas (e.g. bridge and engine control facilities) where increasingly automated operational functions occur. Like other industries, this has reduced crew numbers, altered work demands and moved towards more sedentary, computer-based tasks (Grech, Horberry & Koester, 2008; Mallam, 2014). Ship operations are more automated, centralized and reliable, requiring less direct intervention, though hands-on physical tasks (particularly in the engine and deck departments) are still required. Ultimately, there are now fewer personnel available to effectively delegate and accomplish such tasks (Bloor, Thomas & Lane, 2000; Lundh, Lützhöft, Rydstedt, & Dahlman, 2011).

Physical environments influence both how tasks are completed and the behaviour of people within a space (Engineering Equipment and Material Users' Association, 2010; Meshkati, 2008; Stanton, Salmon, Jenkins & Walker, 2010). Optimizing the physical environment can positively influence worker performance and task execution for safe, efficient system functioning (Aas & Skramstad, 2010; Meshkati, 2003; 2008). The physical work environment of a ship inherently influences how crew carry out their tasks, revealing that physical design can directly impact their safety and productivity (Forsell, Hagberg & Nilsson, 2007; IMO, 1998; Lundh, Lützhöft, Rydstedt, & Dahlman, 2011).

2.1.2. Applying Ergonomics in Practice & Justifying Costs

Applying and integrating ergonomics approaches within an organization has a range of benefits including, but not limited to, reduced work-related musculoskeletal disorders, injury rates and subsequent personal and economic injury costs; reduced employee turnover, absenteeism, errors, training and support; increased productivity, satisfaction and quality of work (Fritzsche, Wegge, Schmauder, Kliegel & Schmidt, 2014; Hendrick, 2003; Goggins, Spielholz & Nothstein, 2008; Maguire, 2001). Ergonomics can be integrated into organizational systems in many different ways. Within large companies and projects a decision must be made about where and how to embed ergonomics. For example, ergonomics can be applied in operations, design, engineering, safety, training, or distributed across multiple groups (Wilson, 1994; 2014). In design development, the earlier ergonomics is applied and utilized in the process, the easier and more effective information can be successfully integrated into a design (ISO, 2002; 2011). The performance and wellbeing of a user are directly influenced by design, while poor designs not fitting user capabilities or goals can have negative effects (Dul, Bruder, Buckle, Carayon, Falzon, Marras, Wilson & van der Doelen, 2012).

Ergonomics is often associated with health and safety prevention issues, while the wider value and marketing of ergonomics as a tool for optimizing cost-savings and productivity is generally not understood (Dul & Neumann, 2009; Jenkins & Rickards, 2001; Zare, Croq, Hossein-Arabi & Brunet, 2015). The discipline is often viewed as a softer science (Hendrick, 1996; Meister, 1999) and the usefulness of ergonomics has been questioned by the design community (Stanton & Young, 2003). Ergonomics is often perceived as secondary to an organization's main goals, only to be added if the timeline and budget allows (Mallam, Lundh, & MacKinnon, 2017a; Norros, 2014). The upfront investment and planning required to include an ergonomics program in an organization may be a deterrent to management and viewed as adding unnecessary costs to a budget. A crucial element of a successful ergonomics program is to have managerial support (Haines, Wilson, Vink & Koningsveld, 2002). Therefore, ergonomics in practice finds itself in a paradoxical situation: in order to prove its benefits within a specific organization, an upfront resource investment is required and must be adequately supported, resourced and sustained in order to show measurable benefits (Vink, Koningsveld & Molenbroek, 2006).

It is critical to demonstrate the benefits of ergonomics in quantifiable cost-savings and tangible performance outcomes (Falck & Rosenqvist, 2012), as good ergonomics is not only appropriately applied knowledge, but should also be cost-effective and practical (Hendrick, 1996; 2008). In recent years cost-to-benefit analysis research has strived to fill this gap by investigating the application of ergonomics across a range of domains. Beevis (2003) and Goggins, Spielholz & Nothstein (2008) found that academic research is generally biased towards demonstrating the economic benefits of ergonomics. It is difficult to accurately assign costs and benefits associated to ergonomics applications, while specifically within the shipping industry there is little data on the economics of ergonomics (Österman & Rose, 2015; Österman, Rose & Osvalder, 2010).

It is imperative for ergonomics applications to demonstrate tangible results and justify an organization's investment. Initial ergonomics interventions should consider the "low hanging fruit" by addressing obvious and easily fixed design deficiencies to display short term results, and ultimately gain creditability with management and other stakeholders (Hendrick, 2008). This result-oriented approach builds relationships and trust that can be leveraged into longer term, more intensive ergonomics applications.

2.2. The Maritime Domain: Merchant Shipping

The maritime domain can be defined as all areas and things of, on, under, relating to, adjacent to, or bordering on a sea, ocean, or other navigable waterway, and includes all maritime-related activities, infrastructure, people, cargo, ships and any other structures (Bucchianico, 2015). The shipping industry is an extremely competitive domain, where a fundamental requirement of survival is maximizing the efficiency of operations (Bhattacharya, 2015). Innovations of marine structures and operational systems have increased performance capabilities and cargo capacities of ships, facilitating the growth of freight traffic and impact on global trade and economy (Maribus, 2010). Today, approximately ninety percent of global cargo trade occurs via shipping, which in 2013 amounted to nearly 9.3 billion tons of seaborne shipments (Stopford, 2009; United Nations, 2014). The global fleet (including oil tankers, bulk carriers, general cargo ships, container ships, gas carriers, chemical tankers, offshore supply ships, ferries and excluding inland waterway, fishing and military ships, yachts, offshore fixed and mobile platforms and barges) recorded a total deadweight of approximately 1.7 billion tons in 2014 (United Nations, 2014) and consists of over 85,000 ships (European Maritime Safety Agency, 2015), 1.2 million seafarers (Lane, 2002) with the number of ports in excess of 4,900 (including inland ports) distributed across 196 countries (World Port Source, 2016).

The shipping industry is an inherently dangerous domain (Lu & Tsai, 2010). Although maritime accidents have steadily declined over the twentieth and twenty-first centuries with shipping becoming a generally more reliable and safer domain (Chauvin, Lardjane, Morel, Clostermann & Langard, 2013), the industries and professions associated with working at sea are amongst the greatest risk for injury and mortality (Roberts, Nielsen, Kotłowski & Jaremin, 2014). As merchant shipping, fishing and offshore exploration operations move further north into isolated polar regions risks will become even higher. Furthermore, incidents involving marine structures have the potential to become catastrophic events (Hetherington, Flin & Mearns, 2006). In the past, shipping accidents such as grounding, collision and sinking have typically only affected a limited number of people (e.g. ship owners, cargo owners, crew and family) (Asyali, 2003). However, as there has been a drastic increase in the physical size and cargo tonnage (including dangerous material shipments) of merchant ships, any single incident has large safety, environmental, economic, legal and social implications which would not have had the same impact with the smaller ships of decades past. For example, the largest container ship in the world in 1972 held 2,950 twenty-foot equivalent units (TEU), in 1996: 6,400 TEUs, 2003: 10,500 TEUs and in 2016, the *MSC Oscar* at 394 meters long, 59 meters wide and holds 19,224 TEUs. Similar trends are seen in passenger ships, with contemporary cruise ships now having a maximum carrying capacity of over 6,000 passengers (e.g. Royal Caribbean International's MS *Allure of the Seas* and MS *Oasis of the Seas*).

Despite the dramatic increase of ship sizes and numbers in recent years, losses have decreased from 1 ship per 100 per year in 1912 to 1 ship per 670 per year in 2009 (Allianz Global Corporate & Specialty, 2012). While there is a declining trend in shipping accidents, total losses of large ships still continue with relative regularity (e.g. total ship losses globally per year 2011-2014: 91, 121, 110 and 75, respectively) (Allianz Global Corporate & Specialty, 2015). As ships become larger in order to increase cargo and human carrying capacities, the consequences of an incident also increase. Not only is a ship itself potentially worth tens to hundreds of millions of United States Dollars, but the financial and social impact of associated insurance costs, cargo value, loss of human life, destruction of the surrounding environment and its related economic activities can have a global reach.

2.2.1. The Human Element Onboard

Seafaring is a unique occupation that has very different working conditions and variables than typical land-based professions. While fatal accidents onboard have been reduced, occupational injury rates are still above those of most land-based industries (Hansen, Nielsen & Frydenberg, 2002; Oldenburg, Baur & Schlaich, 2010). The transient nature of shipping physically and psychologically isolates onboard crew. Work, rest and leisure activities occupy the same confines and can keep individuals away from their home, family, friends and “normal” onshore life and routines for long periods (Louie & Doolen, 2007). Working hours can be irregular and around the clock, disrupting circadian rhythms, creating crew fatigue and stress which are detrimental to operations, overall ship safety and have harmful effects on personal health (Bloor, Thomas & Lane, 2000; Harrington, 2001; Louie & Doolen, 2007). Humans working within moving environments are also susceptible to degraded physical (both gross and fine motor tasks) and cognitive skills, increased potential for whole-body fatigue, motion sickness, slips, trips and falls, and general vulnerability for making errors (Calhoun, 1999; Dobie, 2000; Jensen, Sørensen, Canals, Yunping, Nikolic & Mozer, 2005; MacKinnon, Matthews, Holmes & Albert, 2011; Matthews, MacKinnon, Albert, Holmes & Patterson, 2007; McCafferty & Baker, 2002). In heavy weather (e.g. high winds, waves, rain, low visibility, etc.) the act of standing or walking can be challenging and severely degraded or inhibited by the environmental conditions, let alone the demands of successfully operating or maintaining a ship safely at sea.

Within the engine department, the crew are exposed to additional risks for injury and disease which are associated with the enclosed engine room space and its challenging work conditions (Nielsen & Panayides, 2005; Orosa & Oliveira, 2010). Engine crew are exposed to risk factors such as high noise that can result in permanent hearing loss (Svendsen, 1999) and hazardous chemical compounds found in oils, soot and engine exhaust that can contribute to developing certain cancers (Forsell, Hagberg & Nilsson, 2007; Nilsson, Nordlinder, Moen, Øvrebø, Bleie, Skorve, Hollund & Tagesson, 2003; Saarni, Pentti, & Pukkala, 2002). The harsh ambient conditions can contribute to heat stress and thermal shock (Orosa & Oliviera, 2010), while tasks that involve heavy physical labour can potentially put engine crew in poor postural positions, increasing the risk for physical injury (Lundh, Lützhöft, Rydstedt, & Dahlman, 2011; Seif, Degiuli & Muftic, 2003; Seif & Muftic, 2005).

Improvements in ship design, equipment sophistication and reliability have reduced the frequency and severity of shipping accidents (Allen, 2009; Grech, Horberry & Koester, 2008; Hetherington, Flin & Mearns, 2006). As technology and advancements in engineering and naval architecture have increased the size of ships and reduced labour costs through increased automation, the remaining crew are required to work extended hours and have altered task demands (Barnett, Stevenson & Lang, 2005; Grech, Horberry & Koester, 2008; Lundh, Lützhöft, Rydstedt, & Dahlman, 2011; Progoulaki & Roe, 2011). This has contributed to the dominating trend of human error in accident causation (Hetherington, Flin & Mearns, 2006). Baker & McCafferty (2005) note that although the frequency of accidents is declining, human error by means of inappropriate human responses to threatening situations is identified as a factor in approximately 80%-85% of all maritime accidents. Squire (2013) attributes the remaining 20% to reliability in engineering or technology, such as hull or equipment failure. Kataria, Praetorius, Schröder-Hinrichs & Baldauf (2015) found in an analysis of 129 maritime accidents, that two-thirds involved human-machine interaction and 44% of those involved onboard personnel accidents, revealing the role of poor design in onboard equipment, space design and layout. Dobie (2000) notes that as ship operations and designs evolve, a greater emphasis should be placed on the humans left within the system to maximize safety and efficiency during both routine operations and emergencies.

2.2.2. Rules & Regulations

Mercantile marine shipping is a highly regulated industry (Chauvin, Lardjane, Morel, Clostermann & Langard, 2013). An intricate system of rules and regulations govern minimum standards for ship design, construction and operations involving the IMO, national administrations and classification societies, amongst other stakeholders (Lundh, 2010; Stopford, 2009). The IMO, an organization of the United Nations, is the most influential regulatory body for the global shipping fleet who must adhere to its mandatory frameworks. In addition, national administrative bodies and classification societies establish technical standards and conditions for construction and operation that influence insurance and operation rates. National administration and classification societies differ in their rules and regulations, and shipping companies can choose with whom they register a ship, thus creating an array of potential options and combinations of requirements (Mallam, 2014; Psaraftis, 2002; Rosario, 2000).

Maritime rules and regulations continually develop and cover a vast span of areas, including marine structure design standards, personnel training requirements and operational practices, maritime security, legal affairs and environmental protection. However, maritime safety policy development is a reactive, accident-driven process (Psaraftis, 2002). Almost all important IMO policies have been linked to specific maritime accidents (Schröder-Hinrichs, Hollnagel, Baldauf, Hofmann & Kataria, 2013). What is arguably the most important and influential maritime safety treaty, *The International Convention for the Safety of Life at Sea* (SOLAS Convention) (IMO, 2009), was created in the aftermath of the RMS Titanic disaster in order to establish minimum construction, equipment and operation standards for merchant shipping. Since the early part of the twentieth century an array of regulations have been proposed and developed by a large number of stakeholders. This has created a patchwork effect and contributed to over-regulation, overlaps in regulation, inconsistencies in regulation and gaps in regulation (Psaraftis, 2002). Regulatory bodies have conflicting relationships between balancing safety and economic measures, which often results in inconsistent strategies with unsatisfactory and unintended outcomes (Rosario, 2000).

Shipping's governing bodies have taken a greater interest in the human element within the work system in recent years. The fundamental initiatives of the IMO to address the human element in maritime operations and safety is contained within the *The International Convention on Standards of Training Certification & Watchkeeping* (STCW Convention) as amended (IMO, 2011) and *The International Safety Management Code* (ISM Code) (IMO, 2014). These two documents highlight the dominant role of the human element in the operations and management of the shipping domain (Ashmawy, 2012). Additionally, another

United Nations organization, The International Labour Organization (ILO), adopted the *Maritime Labour Convention* in 2006, which established minimum working conditions for seafarers (ILO, 2006).

The IMO and other organizations have taken some action on more specific concepts involving ergonomics and user-centred applications, acknowledging their importance in contributing to enhanced safety and efficiency in shipping and ship design (e.g. American Bureau of Shipping, 2013; IMO, 1997; 1998; 2004; 2006a; 2006b; 2006c; 2016b; ISO, 2007; Lloyd's Register Marine, 2014). However, the IMO's mandatory rules and regulations for the construction and operation of marine structures (e.g. SOLAS or STCW Conventions) do not include detailed ergonomics support, and are presently only in the form of non-mandatory guidelines (Mallam & Lundh, 2013). Furthermore, the convention that stipulates minimum technical construction standards (SOLAS) and the convention that stipulates training and competencies for safe operations (STCW) do not match, and are not evolving in concert with each other (Mallam, 2014; Mallam & Lundh, 2013).

2.2.3. Ship Procurement: A Brief Overview of Ship Design & Construction

There are four markets of shipping which are closely associated to each other: (i) the newbuild market which creates and trades new ships, (ii) the freight market which trades sea transport, (iii) the second-hand market which trades used ships, and (iv) the demolition, or ship breaking market which scraps ships (Adland, Jia & Strandenes, 2006; Lun & Quaddus, 2009). This thesis focuses primarily on the newbuild market. However, as this research is investigating crew operations and their influence on design and vice versa, the freight market, where shipping operations are carried out, is also of interest (i.e. the experience gained in the freight market by crew can be used to optimize ship designs and finalized structures in the newbuild market).

Shipbuilding is a volatile business highly influenced and impacted by the world economy (United Nations, 2014). The procurement of a new ship is a large-scale, multidisciplinary project that can span years from initial concept to deployment (Rawson & Tupper, 2001; Veenstra & Ludema, 2006). With the opening of international marketplaces, increased domain specialization and economic competition, ship design and construction processes are often split between numerous stakeholders and geographical locations (Mallam, 2014; Österman, Ljung & Lützhöft, 2009). Newbuild ship projects are financed and based on highly researched and scrutinized market predictions and economic forecasting. A ship's design is dependent upon the purpose and demands specified by the investors which best accomplishes their predetermined goals, maximizing their return on investment while meeting the criteria of the pertinent regulatory bodies (Eyres & Bruce, 2012; Schneekluth & Bertram, 1998). Ship owners and investors focus on big picture issues, placing particular importance on a ship's cargo carrying capacity, speed and versatility, rather than on detailed design and operational factors (Veenstra & Ludema, 2006). Subsequently, increasingly specialized, purpose-built ships are developed in order to maximize respective payload in relation to operating costs (Veenstra & Ludema, 2006).

The shipbuilding industry is a heavy engineering business that creates sophisticated products in industrialized countries. Shipbuilding is one of the most open and competitive markets in the world. It is now mainly based in Asia, with Japan and South Korea alone producing two-thirds of the world's ships (Stopford, 2009). The complexity and scale of a newbuild ship project requires a comprehensive and proactive approach throughout development in identifying inter-dependencies and associated risks (Chalfant, Langland, Abdelwah, Chryssostomidis, Dougal, Dubey, El Mezyani, Herbst, Kiehne, Ordonez, Pish, Srivastava & Zivi, 2012). Ship design and construction outwardly appear as exclusively engineering and economically-focused processes. However, the overall project involves strong project management, teamwork, communication, business, economics, art, creativity, leadership and domain experience (Rawson & Tupper, 2001). Veenstra & Ludema (2006) outline a generalized overview of the shipbuilding process (see Figure 2).

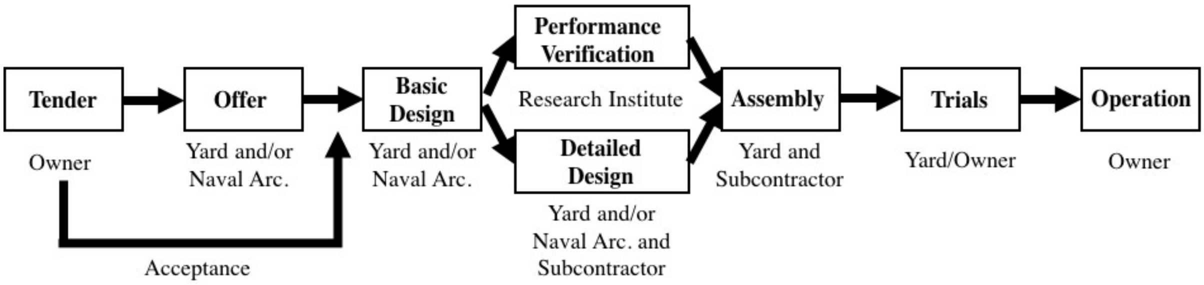

Figure 2. Design related activities in the shipbuilding process (adapted from Veenstra & Ludema, 2006).

After a tender has been awarded to a naval architecture firm and shipyard (or naval architecture firm associated with a specific shipyard), the design phase begins, which is split into two generalized phases: basic and detailed design. The basic design stage develops principle ship dimensions and power requirements that will satisfy a ship's defined performance and techno-economic prerequisites (Molland, 2008). As the design and project progresses from initial general requirements and purpose, basic design evolves into increasingly detailed variables that are introduced and evaluated iteratively throughout the process (Evans, 1959; Han, Abdelkhalek, & Chen, 2014). Sketches and concepts evolve through iterative cycles into more concrete and complete drawings of a ship's layout and GA. This may first take place with pencil-and-paper or immediately using computer-aided design (CAD) software (Pawling & Andrews, 2011). The ship's hull formation, general dimensions and characteristics are established first, creating the overall structure (Eyres & Bruce, 2012). As equipment and system specifications develop it is then decided where and how they fit into the established "container" of the ship, thus creating a Tetris®-like procedure of placement. GA drawings are developed to illustrate the basic physical dimensions and layout of a ship, including side and cross-sectional views of the different compartments, location and arrangement of bulkheads, superstructures and major equipment (van Dokkum, 2011) (see Figure 3). The design phase of a ship can generally vary between 6-18 months with finalized ship design drawings taking hundreds of thousands of man-hours and as a general rule, costs approximately ten percent of the total building price (van Dokkum, 2011).

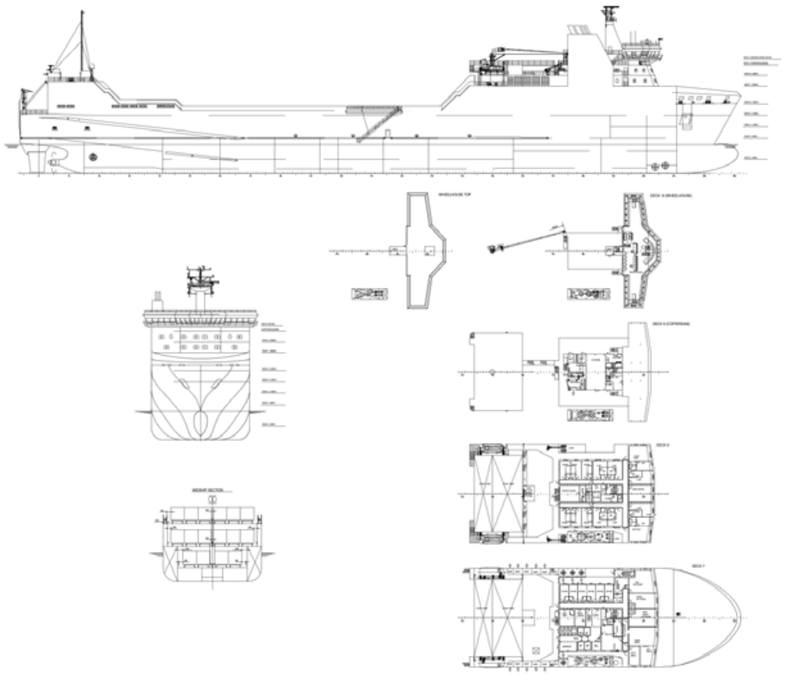

Figure 3. Partial GA drawings for a RO-RO cargo ship.

From the basic and detailed design phases develops a set of ship drawings (general and detailed engineering drawings) and specification lists detailing equipment, system and build requirements which are then used to guide the physical assembly of the structure at a shipyard. The construction time of a ship can vary widely, but generally takes between 6-24 months (van Dokkum, 2011) where materials alone account for 60% or more of the total project costs (Stopford, 2009). After a ship has been constructed sea trials can begin, during which the ship and its systems are tested and refined. Once acceptable to the owner the project is confirmed as completed and the ship is taken into operation.

2.2.4. Accounting for the Human Element in Design & Construction

Shipowners have traditionally focused their investments on increasing efficiency, which has primarily centred on improving shipping technologies, rather than the people working onboard (Bhattacharya, 2015). Similarly, ship designers are mainly concerned with ship powering, stability, strength and seakeeping, with less focus and importance placed on the users who will eventually operate the constructed ship (Andrews, Casarosa, Pawling, Galea, Deere & Lawrence, 2007). Crew are rarely involved in ship design and construction, and are generally only exposed to the system's design configuration late in commissioning, once they perform sea trials or take a ship into operation (Earthy & Sherwood Jones, 2010). User considerations should be accounted for in the design of a ship, as failing to do so could increase the potential for poor design decisions, the creation of hazards, and ultimately, future human error (Asyali, 2003; Méry & McGregor, 2009).

Unfortunately, many contemporary ship designers do not have the experience or knowledge of ship operations necessary to support user needs (Chauvin, Le Bouar & Renault, 2008). Ship designers rarely spend time onboard ships at sea and seldom have the opportunity to form an understanding or empathy of the real working conditions and demands of crew during ship operations (Chauvin, Le Bouar & Renault, 2008). Ship designers are removed from how their conceived end-products are actually used in the real-world. With continually evolving technologies and operational procedures, designers who are disconnected from the realities of onboard demands will never be able to visualize nor create a ship optimized for the physical and cognitive capacities of the user (i.e. crew).

2.2.5. Computer-Aided Design Software: Engineering & Ergonomics Applications

Ship designs are predominately developed through CAD tools. CAD technologies boost productivity, reduce product development time and allow for rapid computation and comparison of many design parameters (Chryssolouris, Mavrikios, Papakostas, Mourtzis, Michalos & Georgoulias, 2009; Eyres & Bruce, 2012). Due to increasingly globalized design and manufacturing, geographically-distributed stakeholders require closer collaborations over a project lifecycle. Various computer supported collaborative design tools are utilized to facilitate effective management and knowledge transfer between distributed stakeholders. Examples include digital visualization systems, data exchange and management platforms and social software for mass, Wiki-style collaboration (Shen, Hao & Li, 2008).

Physical mock-ups and drawings with varying fidelity and scales have been used with input from SMEs to evaluate and develop ship designs and work environments (e.g. Bligård, Berlin & Österman, 2015; Bligård, Österman & Berlin, 2014; Lundh, Paraïso & Mallam, 2013; Novak, Kijora, Malone, Lockett-Reynolds & Wilson, 2010; Ventikos & Sotiralis, 2016; Österman, Berlin & Bligård, 2016). However, CAD technologies have become the norm for naval architects and marine structure design (McCartan, Harris, Verheijden, Lundh, Lützhöft, Boote, Hopman, Smulders, Lurås & Norby, 2014). CAD visualization technologies can be used to facilitate a wide range of user-centred issues in the design and operation of marine structures. This includes such virtual reality applications as qualitative and quantitative risk identification and implementation of risk-based design methodologies, development and evaluation of the design and layout of onboard work environments and equipment, simulation of evacuation, fire and survivability scenarios, and assessment of onboard ambient conditions (FAROS Consortium, 2016; Javaux, Luedtke, Adami, Allen, Denker, Mikkelsen, Lohrmann, Mextor, Sternon, Sobiech, Vanderstraeten, van Goens & Vroonen, 2015; Lossa, Ortiz & Bahamon, 2010; Vassalos, Azzi & Pennycott, 2010). Additionally, serious gaming can be utilized for spatial awareness and familiarization training of ship's crew via game-based virtual reality technologies (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012; Stone, Caird-Daley & Bessell, 2010).

Specific ergonomics CAD software has struggled to gain widespread application in naval architecture (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012). The integration of the human element through CAD software tools is often difficult and ineffective (Feyen, Liu, Chaffin, Jimmerson & Joseph, 2000). User considerations are seldom integrated into the planning processes of production projects (Jensen, 2002), and even if included do not guarantee measurable success (Hall-Andersen & Broberg, 2014; Neumann, Ekman & Winkel, 2009). Designers are not always aware of their influence over the people who will be using their finalized design (Broberg, 1997) and do not have many direct interactions with users to acquire a deep understanding of their work demands (Darses & Wolff, 2006). This can lead to designers relying on their own experience to anticipate user behaviours and practices (Darses & Wolff, 2006). Naval architects are responsible for not only developing a structure optimized from a technical engineering perspective, but also for the working and living environment of the crew. Designers identify a lack of technical tools, domain knowledge and time as barriers to integration of human element issues (Broberg, 2007).

Chapter 3

Theoretical Framework

3.1. Ergonomics & Socio-Technical Systems

A basic description of a system can be defined as a combination of interacting elements organized to achieve one or more stated purposes (ISO, 2010). A system consists of a set of interrelated or coupled activities or entities such as hardware, software, buildings, spaces, communities and people that have a joint purpose (Wilson, 2014). Ergonomics has long been identified as a systems-oriented discipline which examines the interactions between people and a system, rather than concentrating on any individual parts in isolation (Dul, Bruder, Buckle, Carayon, Falzon, Marras, Wilson & van der Doelen, 2012; IEA, 2016; Wilson, 2012; 2014). Wilson (2012) argues that an ergonomics application that does not take a systems perspective is not actually ergonomics at all.

The modern industrial workplace has evolved with increasing complexity where interactions between subsystems are tightly coupled (Perrow, 1983). Various models for socio-technical systems have been created, but all highlight the need to understand interactions between people and elements of a system, including its wider context and environment (Carayon, 2006). The four main elements of a socio-technical system are (i) a technological subsystem, (ii) personnel subsystem, (iii) external environment and (iv) organizational design (Hendrick & Kleiner, 2001). Figure 4 presents a typical model of socio-technical systems and its interacting elements.

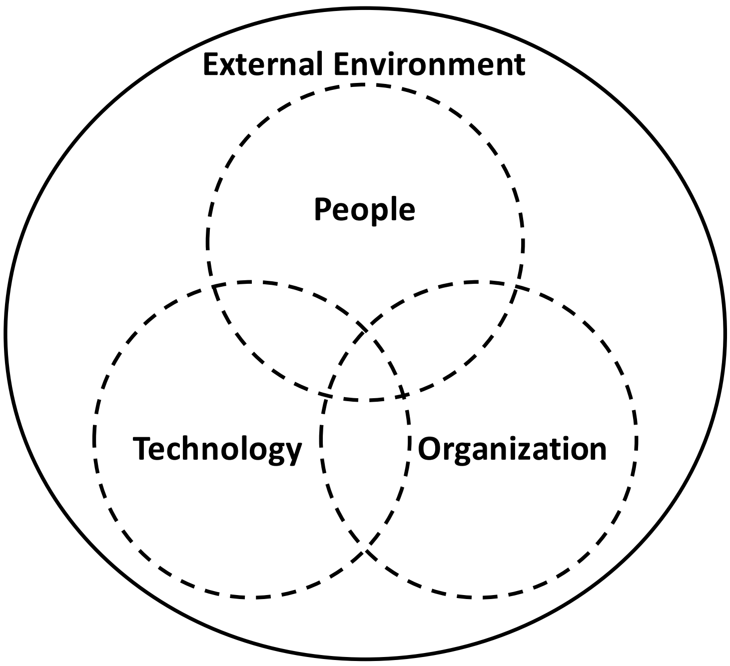

Figure 4. The elements and interactions of a socio-technical system.

A comprehensive ergonomics approach requires that both micro and macroergonomics issues are acknowledged (Hendrick & Kleiner, 2001; Meshkati, 1989; Scott & Charteris, 2001; Zink, 2000). Microergonomics focuses on detailed examinations of interfaces and interactions between humans and elements of a system, while macroergonomics focuses on a broad system-wide view of design, including organizational environments, culture, history and work goals (Morel, Amalberti & Chauvin, 2009). The integration of organizational-level macroergonomics and human-machine level microergonomics in research and practice has proven to be difficult (Karsh, Waterson & Holden, 2014). Zink (2000) suggests that building explicit connections between micro and macroergonomics is important in effective ergonomics application and promotion of the entire field. By beginning with a macroergonomics (i.e. socio-technical) approach, one can better understand a system and its needs, thus more effectively enabling microergonomics applications (Zink, 2000). As macroergonomics is concerned with the design of work systems and account for interactions between people, technology and the physical and cultural organizational system (Kleiner, 2006), macroergonomics promotes a holistic, socio-technical systems perspective to ergonomics application.

The shipping domain is a complex interaction of socio-technical systems on varying levels. For example, individual ships operating at sea have complex internal socio-technical systems that includes social and organizational elements (e.g. onboard crew, work procedures and policies) and technical elements (e.g. equipment, ship, etc.) (Asyali, 2003; Praetorius & Lützhöft, 2011). Furthermore, a single ship operates and interacts within a highly complex and variable external environment (e.g. alternating weather conditions, maritime traffic, geographical environments, operating conditions, etc.). Both the internal and external environments of a ship, its technical equipment and crew are constantly altering and interacting with each other. A socio-technical systems approach provides a comprehensive perspective of the many interrelated variables between the people, technology, organization and greater external environment of complex work systems.

3.2. Creating Systems for Users: Design Approaches

The process of "designing" should be understood as an activity, rather than a product or outcome (Hollnagel, 2014). Design approaches within and across domains can vary widely. Regardless of the discipline, a generalized design process naturally follows a standard development sequence, moving from initial ideas through to prototyping and a finalized design (see Figure 5). Freedom should be left to designers to change goals and constraints as understanding of the problem develops and solutions evolve, while customers should focus on functions and requirements of what a design should do, not what it should be (Cross, 2007). If user's perspectives are not well understood or solicited, designers may not realize or know how to cater to specific user needs (Wilkinson & De Angeli, 2014). Differences exist between designer and user perceptions of a system and it is the user's needs, not the designers, that should be considered throughout the design process (Battini, Faccio, Persona & Sgarbossa, 2011; Hsu, Chuang & Chang, 2000). The beginning, or front end of the design process illustrates the growing importance of the "fuzzy front end" where designers should consider what users of their future design actually want and require (Sanders & Stappers, 2008). Unfortunately, a product or system is rarely designed or studied from the user's perspective, with the majority of the focus placed on technical function and reliability (Sun, Houssin, Gardoni & de Bauvrond, 2013).

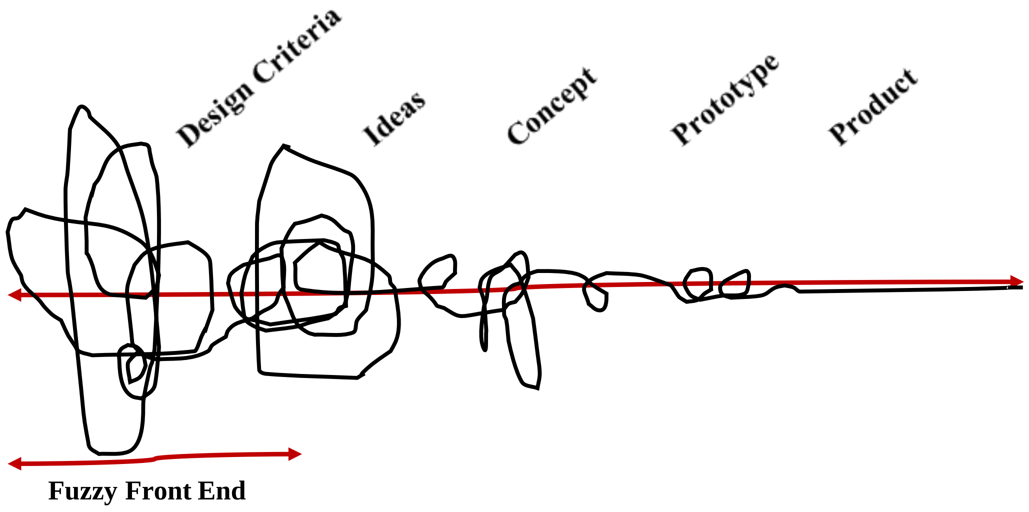

Figure 5. Overview of a generalized design process (adapted from Sanders & Stappers, 2008).

3.2.1. User-Centred, Co- & Participatory Design

User-centred design is a system-oriented approach which requires integration between the human(s), machine(s) and work environment(s) to optimize safety, health and wellbeing by accounting for technological and economic efficiencies (ISO, 2000; 2004). The benefits of thoughtful user-centred design include increased productivity, reduced errors, reduced training and support, optimized project management, improved user trust and enhanced reputation of a system's and organization's reputation (Hendrick, 2008; Maguire, 2001). The user-centred approach evolved from consumer product design processes which focuses on the "thing" being designed and ensuring it meets the needs of the users (Sanders, 2002). For effective implementation of user-centred design, a holistic, iterative design process must be implemented (ISO, 2000).

Critics argue that user-centred design is not sufficiently adequate in addressing the scale or complexities of today's interconnected social environments, people, communities and cultures (Costa, 2016; Sanders & Stappers, 2008). However, user-centred design has evolved and matured into an overarching design philosophy and empathetic approach to ultimately optimize design for user's needs and experiences (Abras, Maloney-Krichmar & Preece, 2004; Costa, 2016; Giacomin, 2014). According to Sanders & Stappers (2008), as emerging design practices require increased focus on designing for people's or society's needs, emotions, experiences and interactions, in order to address these gaps a move must be made towards more participatory design approaches.

Robertson & Simonsen (2012) define participatory design as:

"a strong commitment to understanding practice, guided by the recognition that designing the technologies people use in their everyday activities shapes, in crucial ways, how those activities might be done."

Participatory design reallocates power in design collaborations, where designers no longer "present" solutions to other partners, but rather work together to create and develop solutions (Carroll & Rosson, 2007). Both, participatory design and co-design (or co-creation) are often used as synonyms to describe a design approach which emphasizes the collaborative process between designers and users throughout design development (Halskov & Hansen, 2015; Holmlid, 2009). Participatory design evolved from politicized processes during the mid 1970’s in Scandinavia in an effort to address employment issues and the lobbying for increased employee rights and control over their work, as opposed to co-design which developed apolitically (Gulliksen, Lantz & Boivie, 1999; Kensing & Blomberg, 1998). Gulliksen, Lantz & Boivie (1999) note that as Scandinavian labour laws evolved, participatory design was no longer as tightly associated with political motives, moving participatory design and co-design to virtually identical meanings and purposes, and thus more congruent synonyms.

User-centred and participatory design have similar, overlapping concepts where participatory design may be considered a subset of user-centred design (Gulliksen, Lantz & Boivie, 1999) as one of several methods in its “toolbox” (Abras, Maloney-Krichmar & Preece, 2004). Regardless of the theoretical organization of design approaches, all fall under the user-centred philosophy and strive for optimized design solutions for its users so that an item, system or service is designed for is physically, perceptually, cognitively and emotionally intuitive (Giacomin, 2014).

3.2.2. Participatory Practices: A Fundamental Ergonomics Approach

Good ergonomics is participatory (Wilson, 2014) and a central concept to macroergonomics is that the design and analyses of work systems is a participatory process (Hendrick & Kleiner, 2001). Ergonomics literature refers to the utilization of participatory models and processes to introduce ergonomics as “participatory ergonomics”. Participatory ergonomics initiatives aim to maximize worker involvement in implementing ergonomics knowledge, procedures and changes to their work to improve safety, productivity, quality and comfort based on the fact that workers are expert at their jobs (Goetsch, 2011). Wilson (1995) defines participatory ergonomics as:

“The involvement of people in the planning and controlling a significant amount of their own work activities, with sufficient knowledge and power to influence both processes and outcomes in order to achieve desirable goals.”

Participatory ergonomics can be applied to established and operating systems (e.g. teams, companies, industries, etc.), as well as for conceptual design processes. Its application and purpose in ergonomics, by ergonomists, is the same as the design community: cooperative, collaborative design involving users throughout the entire process. One of the fundamental purposes of implementing participatory practices is to capture the SME’s tacit knowledge, perspectives and experience. Ideally, this information will then be transformed into more user-centred, and theoretically “better” design outcomes.

Establishing a successful participatory ergonomics initiative is essential for creating a climate where participatory design processes can be effectively carried out. Haines & Wilson (1998) proposed a general framework for developing and implementing a participatory ergonomics initiative (see Figure 6). First, an organizational decision must be made to implement some form of participatory ergonomics based on motivational factors and influences (e.g. expert advice, external recommendations, workforce/union negotiations, awareness of ergonomics problems, etc.). Once a decision has been made to implement a participatory ergonomics initiative, methods can be chosen to structure and implement the initiative. As this is an “open” system striving for continuous improvement, the feedback loop is critical to evaluate and influence future decisions.

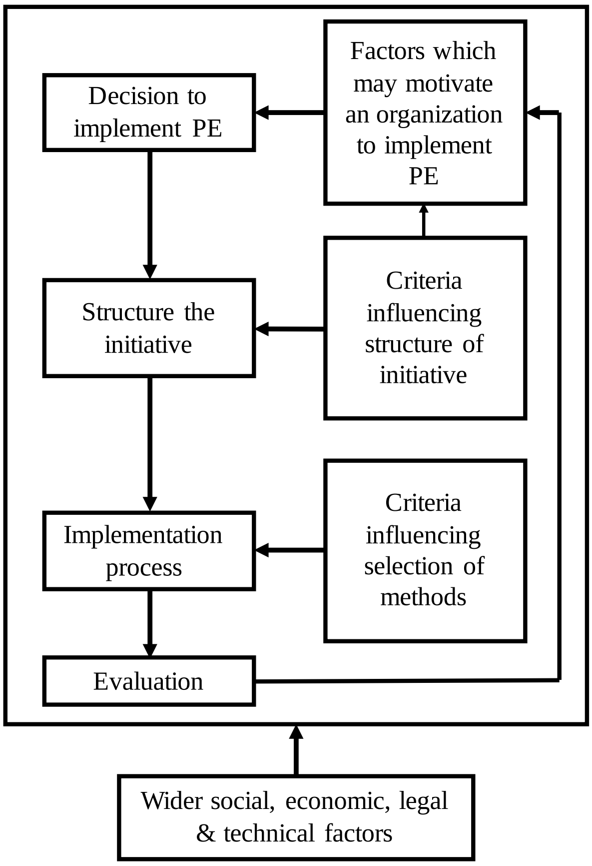

Figure 6. General framework of a participatory ergonomics initiative (adapted from Haines & Wilson, 1998).

Success of a participatory ergonomics initiative is a result of how a process is organized. There are a wide variety of approaches and combinations of variables that may be taken when implementing and structuring a participatory ergonomics initiative (Haines, Wilson, Vink & Koningsveld, 2002; Vink, Koningsveld & Molenbroek, 2006). There is no single “best” way to implement a participatory ergonomics initiative and a strength of utilizing participatory approaches is their adaptability to specific contexts (van Eerd, Cole, Irvin, Mahood, Keown, Theberge, Village, St Vincent & Cullen, 2010). Hignett, Wilson & Morris (2005) found that while most participatory ergonomics projects have a microergonomics component, the overall project is always supported by a macroergonomics framework.

Various research studies and scientific publications have outlined a variety of different factors which contribute to successful participatory ergonomics initiatives (e.g. de Looze, Urlings, Vink, van Rhijn, Miedema, Bronkhorst & van der Grinten, 2001; Haines, Wilson, Vink & Koningsveld, 2002; Koningsveld, Dul, van Rhijn & Vink, 2005; Nagamachi, 1995; St-Vincent, Bellemare, Toulouse & Tellier, 2006; van Eerd, Cole, Irvin, Mahood, Keown, Theberge, Village, St Vincent & Cullen, 2010; Vink, Imada & Zink, 2008; Vink, Koningsveld & Molenbroek, 2006). Critical to any successful participatory ergonomics initiative is attaining and maintaining strong senior management support and being properly resourced at all levels of implementation. To maintain this support there should be open communication with the clients and the demonstration of positive economic cost-to-benefit outcomes. From an organizational and practical implementation perspective a successful participatory ergonomics initiative requires the development of a step-by-step approach with clearly defined scope, goals and participant responsibilities. The creation of a steering group with representative members from all levels of a project or company and direct worker participation throughout the initiative is necessary. Decision-making should be a collective effort, which requires effective and open communication between all stakeholders where iterative evaluations of the effects and side-effects of the initiative are continually analysed. Different stakeholders (e.g. management, designers, employees, ergonomists) should be involved during different stages of the participatory process (Vink, Imada & Zink, 2008). Ergonomists and employees (i.e. users) play a key role in the overall improvement process while designers should be utilized for idea generation and prototyping. Compared to ergonomists and designers, users play a more distributed role across the process (including in analysis, idea generation, idea selection, testing, implementation and evaluation), reflecting the overall user-centred philosophy and goals of participatory approaches (Vink, Imada & Zink, 2008). Barcellini, Prost & Cerf (2015) found that users who participate in design meetings have a distributed style of interaction, not only contributing to functional and operational level discussions (as to be expected), but also conceptual level discussions.

3.2.3. Potential Threats of Involving Users

Notable barriers to the participatory process include lack of a clear mandate, restricted budgets and time constraints, lack of management support, perception of extra work for participants, conflicts with work duties, uninvolved workers becoming envious, lack of worker participation or interest, resistance to change and an ineffective internal responsibility system (Public Services Health & Safety Association, 2010). Although utilizing users in a participatory approach has shown to contribute positively to a project's outcomes, designers can find the process difficult to incorporate into their work due to the increased demand of resources and effort above and beyond the traditional development process (Hawk & dos Santos, 1991; Kujala, 2010). Participatory ergonomics initiatives are perceived to require additional resources, adding time and financial costs to a project or organization (Abras, Maloney-Krichmar & Preece, 2004; Haines, Wilson, Vink & Koningsveld, 2002). However, this perspective lacks a true understanding and foresight for the proven long term advantages and financial savings ergonomics interventions can contribute to (Hendrick, 2008). Critically, ergonomics interventions become less effective and more expensive the later they are applied (Dul & Neumann, 2009).

Involving users during design and engineering phases is particularly challenging because it requires extensive communication (Gumm, 2006), which inevitably leads to discrepancies between different stakeholders (Barrett & Baldry, 2003). Utilizing input from users during ship development limits the number of designs that can be processed within the constraints of a project (Andrews & Pawling, 2003), as it can be difficult to translate collected data from users into design solutions (Abras, Maloney-Krichmar & Preece, 2004). These issues can lead to mixed results and uncertain outcomes within a project or organization (Cole, Theberge, Dixon, Rivilis, Neumann & Wells, 2009; Damodaran, 1996; Heinbokel, Sonnentag, Frese, Stolte & Brodbeck, 1996; Karsh, Moro & Smith, 2001).

3.3. Bridging Gaps: Knowledge Management in Multidisciplinary Teams

Knowledge management is the process by which an organization leverages and extracts value from their intellectual or knowledge assets (Kulkarni, Ravindran & Freeze, 2006). In order for organizations to remain competitive the ability to integrate and exploit intellectual assets and leverage knowledge is critical (Sherif, 2006; Wong, 2005). Organizations with more effective knowledge management systems tend to excel at innovation and are more successful in developing new capabilities when responding to changing environments (Montes, Moreno & Fernandez, 2004). Knowledge is embedded and flows through an organization's employees via intangible assets such as domain expertise and experience (Kulkarni, Ravindran & Freeze, 2006; Rubenstein-Montano, Liebowitz, Buchwalter, McCaw, Newman, Rebeck & The Knowledge Management Methodology Team, 2001). Innovation tends to heavily depend on employee knowledge, expertise and commitment (Youndt, Snell, Dean & Lepak, 1996).

Organizations wishing to implement successful knowledge management must take a holistic systems approach in order to establish adaptive and responsive capacities that can effectively generate, disseminate and absorb knowledge (Parent, Roy & St-Jacques, 2007). This requires an understanding that the people and workplace culture are driving forces in the success of knowledge management initiatives and that organizational issues such as leadership, management and adequate resource support are critical factors for success (Rubenstein-Montano, Liebowitz, Buchwalter, McCaw, Newman, Rebeck & The Knowledge Management Methodology Team, 2001; Wong, 2005).

Large-scale engineering projects such as shipbuilding are inherently complex, demanding heterogeneous resource requirements where multidisciplinary project teams and stakeholders must work together throughout the process (Liu, Chua & Yeoh, 2011). Multidisciplinary teams can have differing perspectives, priorities, work approaches, cultures and professional languages that ultimately hinders ubiquitous understanding and team cohesion (Dougherty, 1992). Due to the noted difficulties in communication and shared understanding between multidisciplinary stakeholders, the creation and management of common factors and platforms, known as "boundary objects", is vital in developing and maintaining coherence across intersecting social worlds (e.g. ergonomics professionals, crew and naval architects) (Star & Griesemer, 1989). In participatory group settings boundary objects facilitate participants in sharing their knowledge across disciplinary and social boundaries (Carlile, 2002; Rose, Homa, Hovmand, Kraus, Burgess, Biswas, Aungst, Cherng, Riolo & Stange, 2015). Boundary objects can create a common language and facilitate joint problem-solving between stakeholders, establishing a concrete means for individuals to share and represent their knowledge in a participatory context (Broberg, Andersen & Seim, 2011; Carlile, 2002; 2004).

Broberg, Andersen & Seim (2011) investigated different types of boundary objects commonly found in participatory ergonomics literature and utilized in ergonomics interventions. These included standardized forms as methods (e.g. documents, injury reports, rules and regulations, questionnaires, usability testing, focus group interviews), objects, models and maps (e.g. prototypes, CAD, computer visualization – 2D, 3D, animation, etc., scaled or full-size mock-ups), discourses (e.g. video recordings of work, questioning situations, think aloud) and processes (e.g. prototyping, testing new ways of working). Participatory design practices typically involve face-to-face interactions between multidisciplinary stakeholders for direct representation and communication where physical boundary objects (e.g. scale models, mock-ups, design sketching, etc.) and/or walk-through scenarios of the real work environment enable designers and users to discuss work issues related to design (Andersen & Broberg, 2015; 2016; Broberg, 2010; Lundh, Paraïso & Mallam, 2013; Lurås, 2016; Österman, Berlin & Bligård, 2016). The use of shared boundary objects such as physical objects and storytelling allows the involvement of non-designers in the design process (Strom, 2007) and facilitates knowledge management within a multidisciplinary project team or organization.

Both the shipping and ergonomics domains have struggled with issues of knowledge management. In the highly international and distributed shipping industry the application of ergonomics principles has failed to reach its full potential in facilitating ship design and operations, or influencing regulatory bodies. A gap between researchers and practitioners has long been identified across domains where new knowledge fails to be utilized in practice (Parent, Roy & St-Jacques, 2007). However, new innovations require those within an organization to move beyond their comfort zone and take on new knowledge and ideas, while the reliance on existing knowledge inhibits development and innovation (Darroch, 2005).

Effective knowledge management of distributed organizations performed on a global level requires that knowledge be transferred from one individual, team, department, or geographical division to another (Argote, Ingram, Levine & Moreland, 2000). Information technology is a powerful tool that can overcome time and distance barriers (Ratcheva, 2009). Information technology also reduces fragmentation between multidisciplinary stakeholders, enabling and mediating knowledge management (Nitihamyong & Skibniewski, 2006; Tanriverdi, 2005). Digital knowledge management tools facilitate users to collaborate, exchange, create and distribute knowledge through peer-to-peer exchanges (Lau & Tsui, 2009). Facilitating knowledge management through information technology and e-learning platforms fosters a constructive, open, dynamic, interconnected, distributed, adaptive, user-friendly, socially concerned and accessible wealth of knowledge (Lytras, Naeve & Pouloudi, 2005).

Distributed, physically removed participation of stakeholders (particularly users) runs against traditional participatory ergonomics frameworks. However, the highly distributed nature of many industries, including shipping and shipbuilding, demands further investigation of how information technology solutions can bridge communication gaps between multidisciplinary, geographically-distributed stakeholders and ultimately facilitate the development of improved design outcomes.

3.4. New Technology Adoption

For a new technology to be successfully adopted it must be accepted and used and by its target population (Venkatesh, Morris, Davis & Davis, 2003). There is typically a substantial delay between the creation of a new technology and its adoption (Doraszelski, 2004). Thus, understanding the factors which influence users to accept or reject a new technology is of great interest to both academia and industry.

Technology adoption can be studied from an individual, group or organizational level (Venkatesh, 2006). A microperspective examines individuals and their choices that contribute to their acceptance or rejection of a particular innovation, while macroperspective examines how innovation diffuses throughout a population (Straub, 2009). A variety of models have been developed investigating the factors affecting technology adoption, particularly in information systems research, which had focused on information management and information technology applications (Chen & Huang, 2016; Venkatesh, 2006). Popular microperspective models include theory of reasoned action [TRA], theory of planned behavior [TPB], technology acceptance model [TAM] and unified theory of acceptance and use of technology [UTAUT], while popular macroperspective models include diffusion of innovation [DOI] and technology, organization and environment [TOE] frameworks (Chen &

Huang, 2016; Ma, Chan & Chen, 2016; Oliveira & Martins, 2011). Although there are a number of technology adoption models proposing differing constructs, there is a basic underlying framework (see Figure 7).

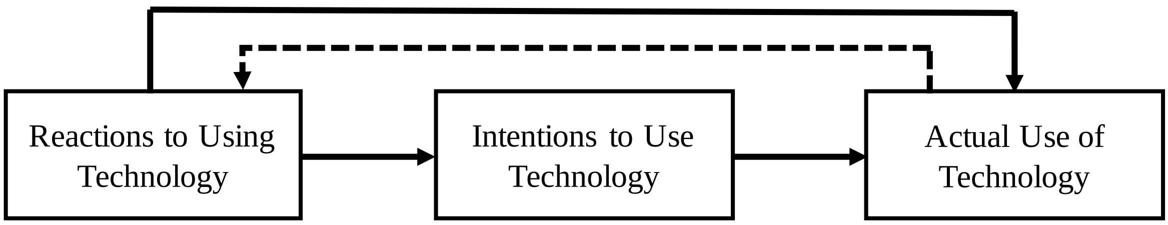

Figure 7. Basic framework of technology acceptance models (adapted from Venkatesh, Morris, Davis & Davis, 2003).

Each model provides a differing construct of factors which affect user adoption intentions and behaviours of new technologies. For example, Venkatesh, Morris, Davis & Davis (2003) compared eight user technology acceptance models, proposing the UTAUT, which describes four core factors: performance expectancy, effort expectancy, social influence and facilitating conditions, and four moderating variables: gender, age, experience and voluntariness of use. Similarly, from a microperspective level, the TRA, TAM and TPB models propose how factors such as perceived usefulness, perceived ease of use, subjective norms, facilitating conditions, self-satisfaction and cost tolerance influence technology acceptance (Ma, Chan & Chen, 2016; Schepers & Wetzels, 2007). DOI and TOE models take a more macroperspective on factors relating to organizational structure and the internal and external characteristics of a system (Oliveira & Martins, 2011).

As technology diffusion throughout a population (macro) is comprised of many sub-processes of individual adoptions (micro) (Straub, 2009) both perspectives are of interest to the scope of this research. From the microperspective, it is critical to understand how individual users (i.e. naval architects, ergonomists, crew, etc.) relate to a new technology and rate such factors as perceived usability and usefulness. From a macroperspective, it is important to understand how the shipping industry relates to new processes and technologies (i.e. ergonomics as a discipline and ergonomics technologies) and influences those within the industry. As individual perceived usability and perceived ease of use are mediated by attitude (Chen & Huang, 2016) and subjective norms (of a domain, industry, culture, etc.) affect attitude (Schepers & Wetzels, 2007) it is important to explore the shipping industry as a whole to provide a deeper understanding and context of influencing factors.

Chapter 4

Methodological Framework

This chapter presents the research approach and tools which were implemented throughout the author's Doctoral research. Elements of this chapter outline the author's entire five-year Doctoral research program, with reference to research published in various peer-reviewed national and international conference proceedings, as well as a technical report prepared for the Swedish Navy and a book chapter for a Nautical Institute publication (see full publication list on pages vii-ix). The primary focus of this chapter is on the findings from the four appended articles which make up this thesis. Three of which were data collections utilizing participants (articles I, II and IV), while one (article III) describes the ergonomics integration strategy and development process which inspired the software prototype, *E-SET*. All elements have contributed towards the author's research education and the greater scientific body of knowledge. Section *4.1. Overall Research Approach* discusses the author's complete Doctoral research program, while from section *4.2. Participants* and onwards details the specific participant sample, experimental design and methods of the four appended articles this thesis is based on.

4.1. Overall Research Approach

The purpose of the author's Doctoral research program was to investigate a participatory approach for integrating ergonomics and user knowledge into the design process to ultimately improve onboard work environments for crew. The research approach has involved a variety of methodologies and specific tools in data collections and literature reviews that have formulated the basis of the proposed integration strategy and development of *E-SET*. Data collections focused on the primary stakeholder groups involved in the system analysis and idea generation phases of an ergonomics initiative: employees, designers and ergonomists (Vink, Imada & Zink, 2008); or in this shipping context, seafarers (users/employees on the ship) and naval architects (designers of the ship).

Upon reflection, the author's Doctoral research program can be divided into three distinct phases which focused on different issues and utilized different data collections to attempt to answer this thesis's overall research questions (See Figure 8). It is important to note that for several of the projects and articles presented here, the author was part of a larger team and not necessarily the main contributor or first author on individual projects and papers. These projects have been invaluable in expanding the author's research scope and adding depth and breadth to his research portfolio. However, the thesis author was the main contributor to the planning, execution of data collections, analyses and writing of the appended articles for which this thesis is based on (presented in bold in Figure 8). The journal articles presented in the author's research timeline reflect the period in which the data collection, analysis and initial writing were performed, and not necessarily reflective of the official journal publication date.

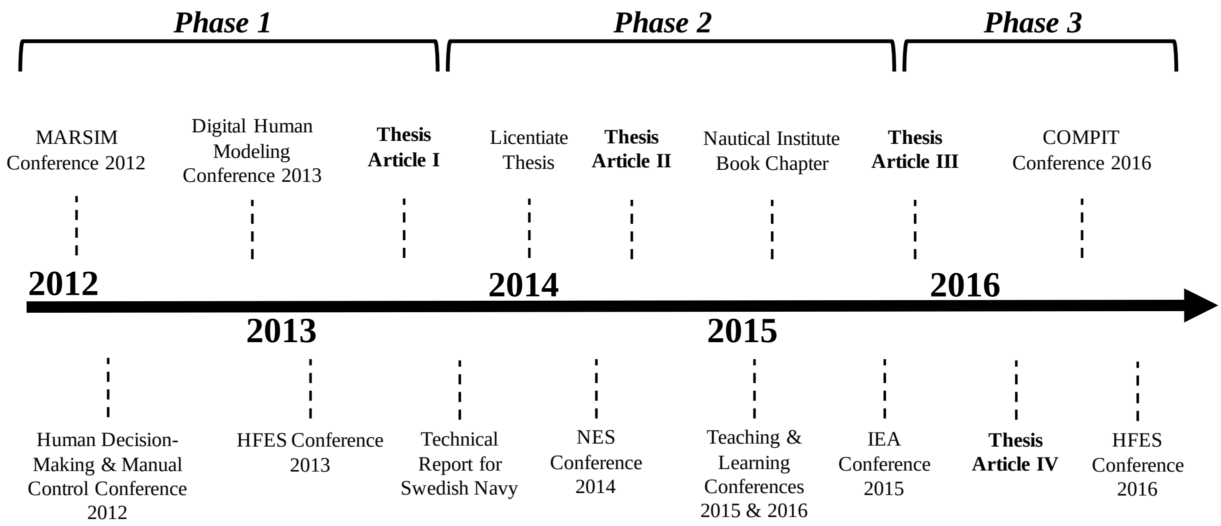

Figure 8. Overview of research publication timeline.

4.1.1. Phase 1 (circa 2012 - 2013)

Initial focus was placed on identifying and exploring technologies which, in the hands of SMEs, could be utilized to improve the evaluation of ship work environments, crew training and safety organization (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012); e-learning and knowledge transfer via digital platforms (Lundh, Blomé, Mallam & Paraïso, 2013); the rules and regulations of ship design in relation to user needs and ergonomics issues (Mallam & Lundh; 2013; Mallam, Lundh & Smith, 2012); and how physical environments of ships influenced how onboard work was performed (appended article I - Mallam & Lundh, 2016). These research projects and publications focused predominately on the engine department and engine crew. Literature reviews established the basis for the conceptual articles and argumentation of rules and regulations, while focus groups and paper-based questionnaires were implemented to collect participant data.

4.1.2. Phase 2 (circa 2014 - early 2015)

The second phase naturally began after the data collection of appended article I, where it was identified that participants (engine crew) communicated and represented themselves and their ideas through sketches and manipulating basic 2D GA drawings. This was further explored with more structured, formalized data collections and research questions exploring GA drawings as a common platform and communication tool to be used between multidisciplinary stakeholders. Phase 2 consisted of investigations involving ergonomists (i.e. the researchers), naval architecture students and crew through traditional face-to-face participatory intervention meetings using drawings and models (Lundh, Paraïso & Mallam, 2013); integrating ergonomics knowledge and user-centred design methodologies in the naval architecture design process (de Vries, Costa, Hogström & Mallam, 2015); and ergonomics education of multidisciplinary groups – ship crew and ship designers (Mallam 2014; 2015; 2016). A field study onboard a RO-RO cargo ship was performed to investigate the differences between its conceptual 2D GA drawings and the constructed reality to better understand the strengths and weaknesses of GA drawings in ergonomics analyses, as well as how crew work in relation to specific design elements (appended article II - Mallam, Lundh & MacKinnon, 2015b). These ideas were presented and explored further in theoretical and review publications at various conferences and a domain-specific shipping publication throughout this period (Lundh & Mallam, 2015; Mallam & Lundh, 2014; Mallam, Lundh & MacKinnon, 2015a).

4.1.3. Phase 3 (circa early/mid 2015 - 2016)

The third phase of the author's Doctoral research consisted of operationalizing the knowledge collected and discussed in the first two phases through developing and testing an ergonomics integration and design strategy, as well as a digital tool as an apparatus to facilitate the established goals of the research program. A major contribution to this phase was appended article III (Mallam, Lundh & MacKinnon, 2017b). This article explicitly details the motivation for the development of the software prototype, *E-SET*, which was created to facilitate participatory design practices and knowledge transfer between multidisciplinary stakeholders. This was further expanded by Lundh, Mallam & MacKinnon (2016) and Mallam, Lundh & MacKinnon (2016) which explored *E-SET's* contribution in optimizing operator performance and safety through participatory ship development practices and social climate within the shipping industry. Appended article IV (Mallam, Lundh & MacKinnon, 2017a) investigated the usability of *E-SET* with naval architecture students to better understand their needs and views in developing conceptual ship designs and how new ergonomics technology could be integrated pragmatically into ship design processes.

4.2. Participants

The research questions of this thesis focused on a target audience who are a difficult sample to recruit. The targeted participant groups are demographically small and specialized professions that require higher education degrees, professional certifications, training and practical experiences. Seafarers are an inherently transient group who are not easily accessible due to unique working hours and travel patterns. Additionally, access to "real-world" onboard data collections by researchers are difficult from both legal and logistical perspectives. These issues contribute to difficulties in participant recruitment and smaller sample sizes for researchers interested in investigating issues in the maritime domain (Hetherington, Flin & Mearns, 2006). Similarly, naval architecture is a highly specialized profession and recruitment of sufficient participants from the professional population within the researcher's geographical location was challenging.

4.2.1. Sampling

Due to the relatively large amount of resources necessary to conduct interview data collections it is often impractical to interview large sample sizes of all types of employees in a system. Thus, a stratified sampling approach was taken. This focused on a smaller sample of different types of employees (e.g. different ranks of marine engineers), offering a practical method to ensure that data collected is representative of the full group of interest (Hendrick & Kleiner, 2001).

Non-probability sampling was implemented for participant recruitment throughout the thesis's data collections, primarily through convenience and snowball sampling. These two sampling methods were utilized to recruit specific groups of students and professionals that were relatively easy to access for the researchers. Leveraging known and relevant contacts and participants helped to extend recruitment throughout their networks (Bryman & Bell, 2011; Krueger & Casey, 2009). Recruitment was performed through solicitation of professional contacts and acquaintances in industry (e.g. shipping companies, safety and training centres, etc.), colleagues in academia and student populations at relevant higher education and training institutes. Participant recruitment was predominantly centred in Sweden, Western and Northern Europe.

4.3. Methodological Tools

The methodological tools utilized to answer the proposed research questions of this thesis were selected to analyse and optimize human-system interactions of ship operation and ship design. The methods deployed in this research are widely used across ergonomics applications and developing systems with user-centred design processes. In practice, different methods should be used together to enhance outcomes (ISO, 2002). The specific tools utilized for each of the appended article's data collections are outlined in Figure 9.

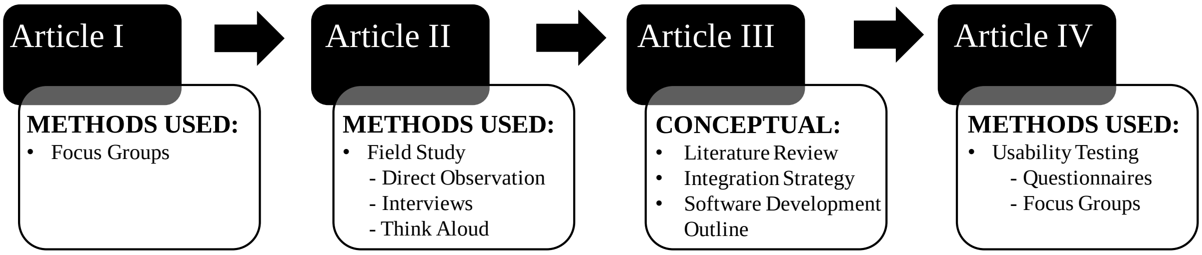

Figure 9. Overview of the methods utilized in each of the four thesis articles.

4.3.1. Interviews

Interviews are one of the most important and common tools in qualitative research for probing the opinions and perspectives of interviewees (ISO, 2002; Myers & Newman, 2007). Interviewing provides a flexible approach for data collection that can be applied to a wide variety of applications to collect large amounts of specific information on a subject (ISO, 2002; Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Due to the face-to-face interactions between interviewers and interviewees, both questions and responses can be discussed in greater detail, allowing for follow-up questioning and explanations where an overall greater amount of information can be elicited from interviewees (ISO, 2002).

4.3.1.1. Focus Groups

Focus groups are a variation of the one-on-one interview approach (Hendrick & Kleiner, 2001). Focus groups provide a collaborative platform where individuals participate in group interviews. Group discussion extracts information and stimulates additional thought and perspectives that one-on-one interviews do not (Krueger & Casey, 2009). They can be used in the development or evaluation phases of design where expert users can discuss the system, functions, usability and design (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). However, focus groups remove anonymity, creating an environment where participants are more prone to groupthink and pressure not to disrupt consensus (Hendrick & Kleiner, 2001). Smaller groups can be advantageous for investigating specialized topics, allowing for increased participant interaction and detailed explanations with a higher likelihood that they will interact and engage with each other (Carey, 1994; Krueger & Casey, 2009).

4.3.1.2. Semi-Structured Interviews

One-on-one interviews, as well as focus group interviews can be designed and delivered in a structured, semi-structured or unstructured (open) approach (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). The majority of the interviews performed in the data collections of the thesis's appended articles were semi-structured. Due to the exploratory nature of the research questions a semi-structured design was preferred over a structured interview, which was considered too limiting and rigid for this application. Unstructured interviews/questioning were implemented sporadically throughout onsite observations during field studies, covered in sections *4.3.3.1. Direct Observation* and *4.3.3.2. Unstructured Interviews & Think Aloud*, below. After the purpose and overall scope of each interview session was established, a script consisting of general topics for discussion was drafted prior to each interview session. This provided a semi-structured framework for conducting the interview, but did not limit discussion if new or unexpected issues came up throughout the process (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). An effort was made to maintain a balance between keeping a discussion on topic, within the pre-established script and scope of the research, and allowing interviewees to explore new and differing issues that developed throughout focus group discussions which the researchers or other interviewees may not have thought of.

4.3.2. Questionnaires

Questionnaires can be utilized in the evaluation process of a system to elicit data on usability issues, user satisfaction, opinions and user attitudes, and can be applied throughout conceptual design processes or the evaluation of existing systems (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Questionnaires are flexible data collection tools that can be applied and customized for a wide number of uses (Czaja & Blair, 2005). There are also a variety of standardized, highly tested questionnaires that were designed and developed specifically for user testing and ergonomics applications (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Utilizing an established, highly tested questionnaire ensures confidence in the tool's validity and reliability, while avoiding the lengthy, resource-intensive process of developing a questionnaire from the beginning.

Appended article IV (Mallam, Lundh & MacKinnon, 2017a) utilized a popular and well-tested questionnaire developed by IBM to assess user satisfaction with system usability – The Post-Study System Usability Questionnaire (PSSUQ) (Lewis, 2002). The version of the PSSUQ selected for this data collection consists of 19 closed-ended questions which have a 7-point Likert scale. The PSSUQ measures overall system usability, usefulness, information quality and interface quality, and reports high levels of validity, reliability and sensitivity (Lewis, 1993; 1995; 2002). The PSSUQ also provides space for open-ended comments in each question to elicit descriptive data (Lewis, 1993; 1995). Additionally, at the end of the survey several customized, open-ended questions were added for context-specific data elicitation. Mixing open- and closed-ended questions on a questionnaire has advantages, as closed-ended questions provide a quantitative basis for data analysis (Czaja & Blair, 2005) which are quick to collate, analyse and manage (ISO, 2002), while adding open-ended qualitative responses to a quantitative framework facilitates more detailed, authentic and unique responses (Tashakkori & Teddlie, 1998; Teddlie & Tashakkori, 2010).

4.3.3. Field Study

The field study approach was implemented exclusively for the data collection of appended article II (Mallam, Lundh & MacKinnon, 2015b) onboard an operational cargo ship. This approach (also known as systematic or naturalistic observation and real-life research) involves going into the field and observing events as they occur under real circumstances in the real-world (Hendrick & Kleiner, 2001). During the onboard field study data were collected utilizing observation, unstructured interviews and think aloud methods.

4.3.3.1. Direct Observation

Participant observation involves collecting information about the behaviour and performance of users whilst they are performing activities in real-world contexts and environments (ISO, 2002). Observational techniques gather data on the physical and verbal aspects of a task or scenario, and while there is no set procedure, can be used at any stage of the design development process (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Direct observation was implemented during the onboard data collection, where the researcher was present, but as unobstructive as possible when observing specific crew tasks and scenarios.

4.3.3.2. Unstructured Interviews & Think Aloud

Field studies provide an opportunity to observe the “real-world”. Habitation onboard a ship at sea provides an inherently isolating environment, thus creating an intensive and immersive experience for data collection. As work and leisure time blends for crew onboard ships, work schedules and processes can be unstructured and fragmented due to their dependence on many differing variables (e.g. weather, port arrival/departure schedules, maintenance issues, etc.). These circumstances naturally provided many opportunities for unstructured interviews with crew. The unstructured interviews, which are more accurately described as periodic unstructured questioning, occurred throughout the observations, during downtime throughout the work day and leisure time (i.e. during dinner at the mess hall, recreational areas, on deck, etc.).

As rapport grew between the researcher and participants, the participants themselves were offering answers and explanations to their work processes that blended unstructured interviewing and think aloud methods during work tasks. Having the participants think aloud while they were performing a task provided an understanding of participant’s thought processes and why they perform certain actions the way they do (Bryman & Bell, 2011; ISO, 2002). This provided deeper insight into their thoughts and perspectives on specific issues and processes throughout the field study observations, eliciting a richer data set.

However, the very presence of an outside entity, such as a researcher, who is known by crew to be observing and documenting their processes can ultimately bias and effect events (Hendrick & Kleiner, 2001). The researcher was acutely aware of his presence and effect on the crew and work environment, and thus attempted to balance unobstructed observations with eliciting deeper data collection through unstructured interviewing and think aloud techniques.

4.3.4. Task & Link Analysis

Task and link analyses were two tools integral to the organization and visualization of user tasks implemented throughout this thesis’s data collections. There are a variety of task analyses techniques, however the overall goal is to describe and represent how the activity of interest is performed (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). This was utilized in initial literature reviews to classify types of work onboard ships and specific crew work tasks, as well as during data collections to organize crew processes when conducting interviews, focus groups and onboard observations.

By knowing who, what, where, when, why and how users carry out their work tasks via task analyses, their spatial movement patterns can then be mapped and visualized through link analyses. Link analysis is a task description method that produces more generalized summaries of activities performed by users, focusing on operator actions rather than work-defined tasks (Hollnagel, 2012). Link analysis provides immediate and useful output that can clearly visualize concepts and identify potential problems during the design and evaluation process by investigating “links” or connections in a system, determining nature, frequency and importance (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Today, this method is predominately used for digital interface design, however link analyses have been used to optimize physical work spaces for over a century (Gilbreth & Gilbreth, 1917; Price, 1989). Implementing task and link analyses in tandem provided a method to first organize a large number of complex user tasks (via task analyses) which are fundamental in understanding work demands; then visualize and map the spatial movement of these tasks throughout a physical space (via link analyses).

4.4. Data Analyses

Data collected from the interactions and observations of participants across each research study was captured in several different forms. All structured interviews and focus groups were audio and/or video recorded and were later transcribed verbatim. Participant sketches, notes and GA drawings that were manipulated by participants were collected or photographed in order to clarify and strengthen verbal transcriptions. The onboard field study included detailed analysis of the physical work environment, including still photography, video recording and measurements of the workspace and equipment. Some unstructured interviews and observations were captured by audio or video recording, however, information was most often recorded in note form by the researcher due to their sporadic and unplanned nature.

4.4.1. Grounded Theory

Grounded Theory was used as a data analysis technique for collected interview data throughout this research. Grounded Theory is a form of qualitative research developed for constructing theory that is grounded in data (Corbin & Strauss, 2015). Grounded Theory strives to construct explanatory propositions to which the real-world corresponds, by allowing concepts to emerge from data (Corbin & Strauss, 2015; Patton, 2002). Grounded Theory allows for the development and revision of emerging concepts throughout the research process, achieving greater precision and consistency in the data (Corbin & Strauss, 1990).

Theory was built from collected data by organizing information into codes and categories (Glaser & Strauss, 1999). Memos provide a base for the formulation of data coding. Open coding (breaking data apart to generate initial concepts) and axial coding (developing and relating concepts into larger categories) were used to develop a basis for core categories and the creation of more general theoretical frameworks relating to engine department function and design (Corbin & Strauss, 2015). Data collection and analyses cycles were terminated upon sufficient saturation of concepts, ensuring no additional data were found which could be developed further (Corbin & Strauss, 2015; Dey, 1999; Krueger & Casey, 2009). The data were coded and analysed using qualitative data analysis software (MAXQDA 11, VERBI GmbH, Berlin, Germany).

4.5. Procedure

4.5.1. Article I

4.5.1.1. Participant Overview

Nine male marine engineering graduates with seafaring experience (Age: 37.2 ±13.4 YRS; Work Experience: 16.8±14.4 YRS) participated in this study. Each focus group consisted of three individuals. Volunteers were recruited from Northern and Western Europe (Nationality: 6 Swedish, 2 Dutch, 1 British). Participant recruitment was a stratified sample representing the majority of positions of an engine department, ranging from chief engineers to cadets (2 chief engineers; 2 second engineers; 1 third engineer; 1 fourth engineer; 1 senior mechanic; 2 cadet graduates).

4.5.1.2. Experimental Protocol

The nine participants were divided into three different focus groups, each focus group consisted of two sessions (see Figure 10). On average, Session 1 lasted approximately seventy-five minutes, while Session 2 lasted approximately thirty minutes. The goal of session 1 was to establish a baseline understanding of engine department operations as a point of departure for exploration into physical design. First, participants were asked to clarify operational requirements and establish common criteria of engine control operator roles and their performed functions, then clarify and discuss how they saw themselves and team members within the work system. Second, participants described their perspectives on key issues of engine department control operations, focusing on how ship GA arrangement influences the organization and execution of their work tasks.

Session 2 began with a review of the topics covered during Session 1. This allowed participants and researchers an opportunity to review, verify and clarify the main discussion points of the previous session. Participants were then given a case study that required them, as a team, to analyse an engine department and engine control facility of a ship from GA cross-sectional paper drawings. This exercise assessed how their design criteria formulated in Session 1 applied to a common practical example. In addition, it was meant to activate additional discussion, clarify concepts and allow participants to further explore control facility design properties through descriptions and drawings. Participants were supplied with large sheets of paper, markers and white boards in order to sketch their control facility designs and illustrate ideas. The session concluded with a discussion of the overall process, key engine control design parameters and future directions of the profession and shipping domain.

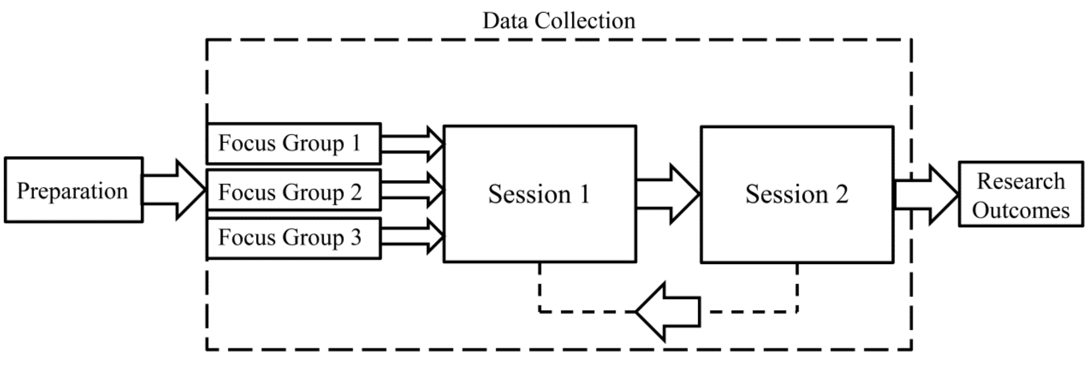

Figure 10. Outline of experimental protocol of article I data collection.

4.5.2. Article II

4.5.2.1. Field Study

A RO-RO cargo ship (Gross Tonnage: 23128.0 Metric Tons; Overall Length: 191.8 meters; Breadth: 26.4 meters; Draft: 7.8 meters) built and in operation since 2006 was used as a case study. Onboard data were collected over a period of eight days in Fall 2014 during the ship's operation in the Gulf of Bothnia, Baltic and Kattegat Seas. During this period there were stops at five ports in three different countries.

4.5.2.2. Participant Overview

During the data collection there were a total of fifteen crew onboard (plus one researcher). This number represents the total ship's compliment. The crew were divided among various divisions, including the navigation, deck, engineering and steward's departments. Although the researcher had contact with all crew to varying degrees throughout time onboard, the focus of the research was on the engine department. The engine department specifically consisted of six crew (1 chief engineer; 1 second engineer; 1 third engineer; 1 motorman; 1 electrician; 1 cadet).

4.5.2.3. Experimental Protocol

The onboard data collection was divided into three broad categories of interest. The first was to perform an onboard physical work environment analysis, mainly focused on the ship's engine department. A detailed analysis of all of the engine room compartments was performed, including the engine control facilities and surrounding areas throughout the ship where engine crew travelled through and performed work. Physical characteristics of each area, including its dimensions, type of equipment, auxiliary installations (e.g. piping and electrical systems) and ergonomics considerations were documented in detail.

Secondly, a comparison was performed between the ship's 2D GA drawings and the constructed reality of the ship using data collected from the onboard physical work environment analysis. This investigation aimed to document the differences between the conceptual drawings and reality, whether the constructed ship and physical work environment differed from its intended design, what information was present or missing and what ergonomics implications this has for the design process.

Thirdly, to complement the physical work environment analysis, each engine crewmember was interviewed (both in semi-structured interviews and unstructured questioning) and job shadowed over the eight-day data collection period. This provided a more comprehensive approach in understanding the relationship between the built environment and system operations from subject-matter experts in real working conditions.

4.5.3. Article III

Article III presents a literature review and rationale which motivated both the ergonomics integration strategy developed specifically for ship design and its influence on the development and functions of the software prototype, *E-SET*, which was created and tested throughout this research program. Therefore, this article did not have any specific data collection or method implemented.

4.5.4. *Article IV*

4.5.4.1. Participant Overview

Thirteen male volunteer participants were recruited (age: 25.3 years ± 2.3 years) from a population of final year students in the Naval Architecture and Ocean Engineering Master's program at Chalmers University of Technology. As a requirement for admission to the graduate program all had completed previous Bachelor's degrees in various engineering and science disciplines: including, mechanical (7), oceans and marine engineering (2), structural (1), civil (1), science (1) and unspecified (1). The participants did not have previous industry work experience or any formal educational exposure to ergonomics concepts or methods. This research project was not formally part of the course content or student evaluation. The researchers were invited to the course by its professor; student participation was voluntary and was not connected to, nor influenced their academic evaluation.

4.5.4.2. Experimental Protocol

The experimental protocol for article IV's data collection was designed as both proof or concept testing for the software prototype, as well as usability testing with its targeted user group. The experiment was divided into four phases (see Figure 11).

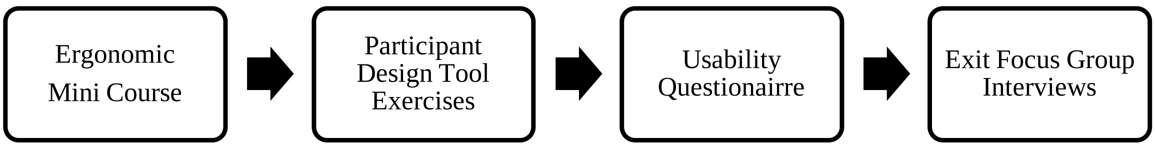

Figure 11. Outline of experimental protocol of article IV data collection.

Participants first attended a four-hour ergonomics mini-course organized by the researchers consisting of traditional classroom lecturing, interactive group work and discussions. The course had been developed over several years as a workshop to introduce and engage naval architecture students to ergonomics concepts which could be implemented into their final year ship design projects.

Following the mini-course participants were brought into a computer laboratory and introduced to the software prototype and testing protocol they would complete. Participants performed the testing protocol on identical laboratory laptops equipped with a wired scroll-wheel mouse and the program preloaded and opened on a computer (64-bit Windows operating system and graphic card; 44 cm screen, 1920 x 1080 HD resolution, Windows 7 operating system, Intel CORE i7 processors).

Four separate exercises were presented to participants in text format within a paper document. These exercises were designed to have participants perform various functions, retrieve and interpret information and explore the 2D and 3D models. Additionally, each exercise requested participants to navigate extensively through the program to login, logout, upload, open and save various files both to test its functions and its graphical user interface (GUI).

Upon completion of the four exercises participants were administered a standard satisfaction questionnaire (PSSUQ) to assess user satisfaction of system usability. Finally, data collection ended with exit interviews. Participants and researchers engaged in a semi-structured focus group consisting of open-ended questioning in order for participants to elaborate upon their questionnaire responses and overall experiences.

Chapter 5

Results

This chapter includes selected key findings from the results reported in the four appended articles.

5.1. Creating Flexibility in Operations: Early Design Decisions Matter

Results from articles I and II collected from ship's crew as SMEs described their onboard work demands and relationship with the design of the physical work environment. This reveals how fundamental design and layout properties of a ship's structure inherently influence how individuals and teams function within a ship system and its physical space. The concept of flexibility of operations (referred to in the article I as "operational flexibility") within physical design was a dominant theme throughout interviews and field study data collections. Participants described that the physical design and layout decisions made in a ship's GA drawings impact how users are able to organize and accomplish their tasks.

Participants detailed how the physical design and layout between different ship areas, equipment and crew can positively or negatively impact work organization, efficiency, and crew health and safety. Through the context of physical design, participants described that the work environment requires inherently adaptable properties that allow crew to create flexibility within their work organization and task execution. Due to the diverse number of variables present throughout a ship's operations, including voyage conditions, weather, geography, traffic density and maintenance schedules, crew have differing demands and focuses which are frequently changing. Expert users must accomplish tasks which are dependent on a particular situation in time. They must mitigate threats to safely and efficiently run an engine department, thus wanting "flexibility" in their task organization and execution, including the work environment they perform in. The term "flexibility" was used broadly to encompass socio-technical concepts from work organization and crew resource management, to utilization of technological solutions and desirable physical ergonomics practices within these workspaces.

Ships and their facilities are common, shared work areas. In the case of the engine department, its control facilities, engine rooms and various work sites throughout a ship are occupied and operated by a variety of highly trained expert individuals, with continuously altering crew combinations and therefore team dynamics. These crew have the same principle tasks and goals; safe and efficient operation. However, work organization (i.e. work as done versus work as imagined) can differ greatly, and thus requires a flexible and safe work environment design that fits the work to all its crew.

5.1.1. Ergonomics Integration During Early Structural Design

Study participants described how location, access and proximity of different areas and equipment throughout a ship's structure effected and influenced their work processes. GA decisions made in the early stages of a new build project fundamentally effect physical linkages, access, proximity and interactions that formulate the basis for how a crew functions within a system. For example, trade-offs between the engine control facilities location relative to key areas of a ship impacts an engine crew's possibilities to organize manpower and execute operations. Therefore, an optimal physical environment creates an adaptable, flexible platform which an expert user or team of expert users implement their preferred operational parameters and work organization.

The findings from articles I and II reveal how crew related to different physical areas of a ship and how these areas were connected through physical (i.e. manned areas, walking between areas/equipment) or technological (i.e. use of computerization and mobile devices for control and communication) relationships. As the primary research participants were marine engineers, both physical and technological connections are critical for bridging spatial gaps between other crew, equipment and areas throughout a ship. Participants described the relationship to relevant areas of a ship by describing a holistic perspective to ship "mapping". Physical linkages, inter-departmental ship communication and mobile data retrieval between different areas of interest, equipment and other crew were described to be important to engine crew in varying ways both on and off duty.

Figure 12 reveals an overview of different areas of a ship most important to the engine crew. From a more global to local perspective this entails work and logistics on the levels of inter-department logistics, intra-engine-department logistics, and site-specific microergonomics. Inter-department logistics and work concerns the movement of the engine crew outside of the engine rooms and engine department. This can include other operational departments (i.e. bridge, deck crew, etc.) or areas of a ship such as crew accommodation. Intra-engine department logistics and work refers specifically to the movement of personnel and equipment within and throughout the engine department and engine rooms. Site-specific work refers to the individual areas or equipment in which work is carried out either within the engine department (intra) or in other areas of a ship (inter).

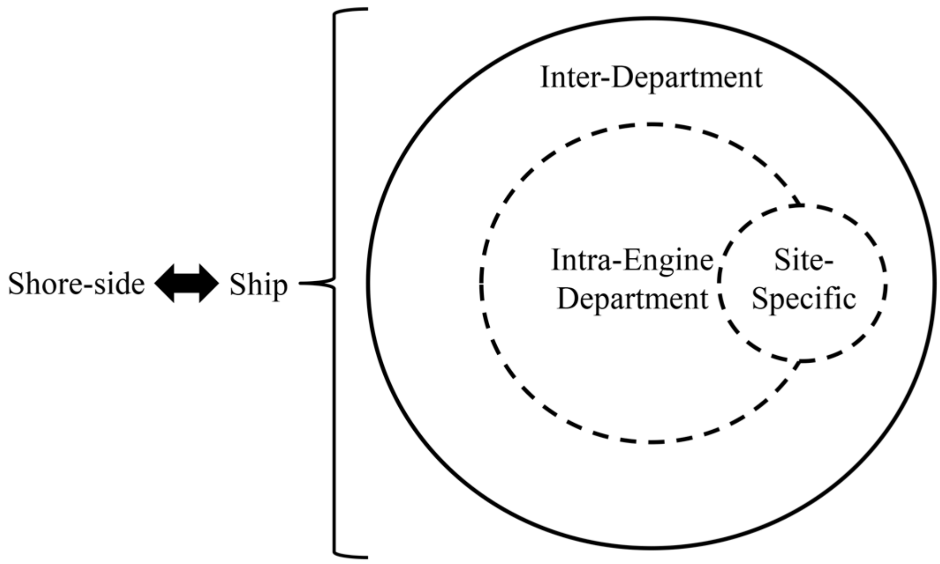

Figure 12. Key areas onboard a ship pertinent to engine crew work and movement.

Permeating these three levels is shore-side to ship connections (and in some circumstances supply ships) onto the ship, and vice-versa (e.g. transport of supplies to/from ship, berthing, bunkering, high voltage connections, etc.). This is generally outside of the responsibility of the engine crew, however designing efficient supply chain logistics from shore-side-to-ship-to-engine department can increase efficiency and reduce physical work and impact on crew. For example, transporting heavy spare-parts from shore-side via a crane, directly to the engine department decks and storage areas within the ship, thus bypassing the need for manual materials handling by crew.

The results of article II reveal how crew either work around poor designs or modify a ship's physical onboard layout to better suit their work after a ship is put into operation. Differences between the original design and how the structure was actually used by crew can be divided into two categories: (i) *the intended design failed to adequately facilitate crew and/or ship demands*, or (ii) *the design did not consider certain crew tasks at all*. Crew designed and built solutions were generally rudimentary and completed at sea (rather than during scheduled in port repairs/retrofitting) after the ship's construction. Crew-initiated solutions were ultimately improvements on the original construction, however were less elegant and effective than if they had been considered during original design and implemented during the original construction of the ship.

5.1.2. Practical Design Input: Hub-&-Spoke Logistics Mapping of Crew Work & Movement

Although a ship's crew have specific routines, tasks and maintenance schedules (varying in frequency between daily, weekly, monthly, yearly and multi-yearly events) it is difficult to categorize a typical work shift into consistent task lists and daily operations. There is planned and unplanned maintenance of equipment, while port calls (entering and exiting ports) are required to be completed at varying intervals throughout operation. Instead of creating an exhaustive list of task analyses, it was found more effective to communicate in terms of work task locations, logistics and processes. Thus, by relating crew work directly to physical ship locations and design properties naval architects are potentially able to translate this tangible information easier into their design work.

Engine crew described their work locations within a ship's structure in a hierarchy of several key nodes. These key nodes are first visited before crew are dispatched throughout the ship for site-specific tasks on equipment, systems or equipment logistics, similar to hub-and-spoke distribution. The engine crew described different hubs in their work environment that were visited before travelling along spokes for site-specific work tasks. This was generally described in equipment logistics and maintenance tasks, but also extended to different areas of the ship (i.e. leaving one's personal cabin at night to check the engine control facilities). For example, the engine crew's workday generally begins with a trip to the locker room to change into their work clothes. This is followed by entering the engine control facilities where crew are briefed on the current status of the system and plan their shift. Work is delegated and discussed between the team before travelling off throughout the ship structure to complete their work tasks. The third engineer described that most onsite manual or maintenance tasks carried out in the engine rooms first require a trip to the workshop, where the appropriate tools would be collected, stating: *"from the workshop you load up a bucket of tools for wherever you need to go"*. Similarly, a trip to/from the storage area for spare-parts or equipment would be necessary before travelling to a specific work site.

Stores and equipment logistics were described and planned by crew in a similar way as their own personal movement. Stores and equipment are transported on a ship from shore-side docks via cranes and deposited on the main deck of a ship. It then has to be transported down multiple levels to the entrance of the engine room and distributed to the appropriate site or down one additional deck level to the main storage area until it is needed. Transportation of heavy and awkward equipment must be thoughtfully planned for movement throughout a structure. Links between key nodes should be mapped and provide clear unobstructed routes which permit easy physical flow and takes advantage of lifting aides (supply hatches, overhead cranes, chain blocks, etc.) to facilitate movement from node to node. The engine crew noted that ease of equipment movement to/from the workshop, storage area, and equipment washing area were critical for their work tasks and logistical flow throughout the engine rooms. Figure 13 visualizes equipment transport throughout a deck of the engine room using link analyses over rough sketching and a ship's GA drawing.

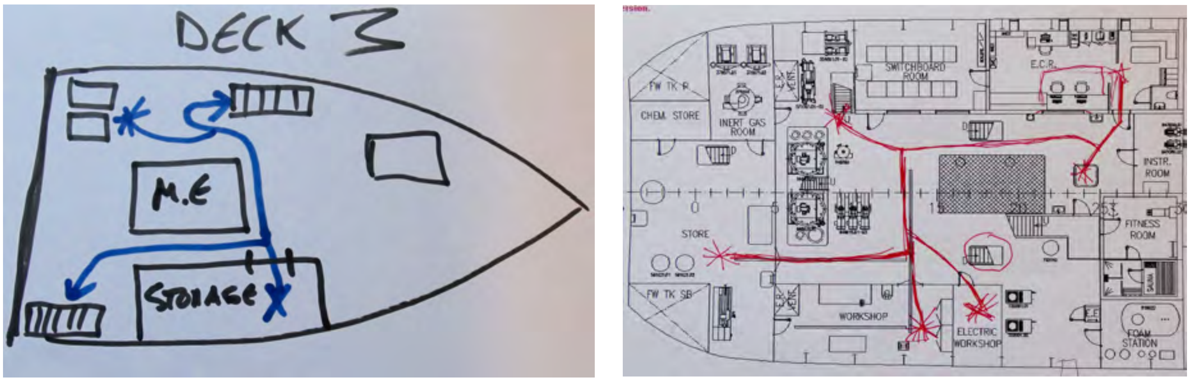

Figure 13. Crew movement mapped by sketching (left) and on GA drawings (right).

5.2. Utilizing GA Drawings for Ergonomics Analyses & Input

Differences between the physical characteristics of a ship's GA drawings and the constructed work environment were discovered in article II. As its name suggests, GA drawings are a general and incomplete representation of the finalized work environment. The GA drawings primarily detail the hull structure, divisions and dimensions of different compartments throughout the ship, including the location and type of primary equipment and operational systems. Additionally, information regarding space and clearance levels between equipment, crew passageways, emergency exits, stair and door placements can be derived from GA drawings.

The onboard data collected reveal that although the primary, large equipment and operational systems were accounted for within the GA drawings, numerous auxiliary equipment and installations are not included. By comparing the GA to reality, what first looks like adequate clearance between equipment and unobstructed passageways for crew or equipment logistics is, in reality, occupied by various installations. These auxiliary installations are developed throughout detailed design in detailed engineering drawings, and are typically never included in GA drawings. The design and placement of items such as piping and electrical systems, manual valves, switches, lifting aides and smaller equipment installations impacted the finalized dimensions of work areas and passageways, revealing many cases of impeded access to equipment throughout the engine rooms.

Figure 14 demonstrates a typical case of a lack of auxiliary installation detail in GA drawings compared to the finalized work environment (the arrow superimposed over the GA drawing indicates the position and direction the photograph – as seen directly below the GA drawing - was taken from). In this example, the midsection of deck 1 is magnified to present a section of the engine room where the fire, cooling and ballast pumps are located. The GA drawing illustrates an open area between the large ballast tanks where only the pump machinery and an overhead lifting aid are included. The information derived from this GA drawing indicates that there is essentially unobstructed access for crew and equipment movement between each pump and the main area of the engine room. As revealed by the photograph, reality is very different. Large deck-level piping and valve installations, as well as overhead piping and overhead electrical tray systems severely alter the finalized work environment, dimensions and access possibilities.

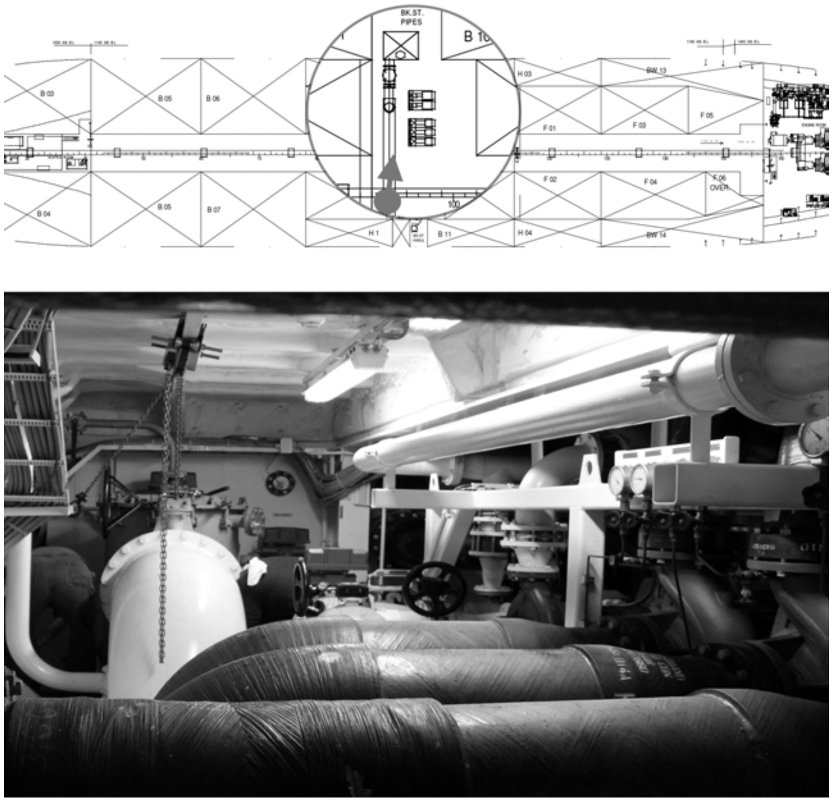

Figure 14. Absence of detail in design: GA drawing versus finalized construction.

Additionally, the comparative analysis showed that the measurements of equipment components, size and shape, distance between equipment and passageways, flooring features, door sizes and stairway characteristics (width, railings and number of stairs in each flight) were not accurately described in the GA drawings. Analysis of the GA drawings reveal that the placements of structures within the ship were used more as “placeholders” to represent where equipment and components were to be installed and not completely representative of the finalized construction and work environment. The differences found between the GA drawings and the constructed ship impacted the finalized onboard work environment, ultimately imposing negative operational and safety implications for crew that were not initially foreseen in the GA design.

5.3. Developing a Participatory Design Software Solution

Based on the findings of appended articles I and II, GA drawings were found to be an effective boundary object and common platform for multidisciplinary stakeholders to communicate design issues. However, consistently organized and executed participatory design meetings and decision-making throughout the entire ship development process is not a practical or sustainable solution due to the geographically-distributed nature of project stakeholders and work processes. Thus, the findings of appended articles I and II suggested that to promote participatory design throughout ship development it is necessary to create a solution that addresses and bridges the professional and physical gaps impeding stakeholder communication.

Appended article III details the purpose, functions and motivating factors for developing the software prototype, *E-SET*. The creation of *E-SET* was a manifestation of the findings from appended articles I and II, which integrated paper-based GA drawing analysis and in-person focus group methods into an online platform. Digitized 2D and 3D renderings of a ship's structure aim to allow greater insight and opportunities for input into the design and layout of onboard work environments. This is achieved by visualizing both the physical environment, as well as crew work tasks and movement throughout a ship's structure. *E-SET* was developed to be a virtual meeting platform and visualization tool to facilitate communication processes between multidisciplinary stakeholders, aiding ergonomists and crew in effectively participating and communicating with designers throughout ship development. The role of *E-SET* and its functions are discussed in detail in section *6.2.2. The Role of Technology in Facilitating Participatory Processes.*

5.4. Usability Testing & Technology Adoption

Article IV tested the usability of the visualization software prototype, *E-SET*, and explored new technology adoption amongst naval architecture students. Clear trends were found during the data analysis and reveal the participant's perspectives regarding overall usability, purpose and value of the program in their design work. Overall, the PSSUQ scale and subscale items report a generally positive perception of *E-SET's* usability. Results indicated an overall mean score of 2.63 (see Table 1). Lower scores are an indication of higher usability and user satisfaction on a 7-point Likert scale (1: Strongly Agree, 2: Agree, 3: Somewhat Agree, 4: Neither Agree or Disagree, 5: Somewhat Disagree, 6: Disagree, 7: Strongly Disagree). Relative comparison between the three subscales reveal "interface quality" items having the highest mean score. The highest single item mean scores of the three subscales were all items of "interface quality" (item 16: $\bar{x}$=2.92; item 17: $\bar{x}$=3.00; item 18: $\bar{x}$=4.23). The "system usability" and "information quality" subscales were reported more favourably, with the lowest single item response scores reported from ease of learning and understanding *E-SET* (item 7: $\bar{x}$=1.62; item 13: $\bar{x}$=2.08).

Table 1. Post-Study System Usability Questionnaire results.

	MEAN	SD
Overall Scale (Item 1-19)	2.63	0.55
System Usability (Item 1-8)	2.39	0.36
Information Quality (Item 9-15)	2.43	0.21
Interface Quality (Item 16-18)	3.38	0.60

The most negative and reoccurring responses from the PSSUQ and open-ended responses from participants focused on the visual theme and interface of *E-SET*. Participants generally responded positively to the program, its purpose and functions, but not to the GUI or visual presentation. The open-ended feedback focused on the poor interface colours and insufficient labelling of the ship's technical specifications, equipment and spaces. The ergonomics tools of *E-SET* were reported to be easy to use, interpret and of value to their design work. However, the technical information of the *E-SET's* 2D and 3D ship models were lacking. Interestingly, the simplicity of the low-fidelity 2D and 3D ship models, purposefully created in this format, were not viewed as a negative characteristic. Participants found the visual detail of the 2D and 3D models adequate, and did not negatively comment on absence detail in the digital renderings; for example, a piece of machinery being represented as a rudimentary, smooth-faced cubic object. Although, participants noted that they wanted technical information included within the models in order to readily identify equipment (e.g. via text labelling).

5.4.1. Adding Value to Design Work?

In both the open- and closed-ended written questions, as well as the focus group discussion sessions, participants were asked their perceptions on the potential added value of *E-SET* and general ergonomics concepts to their design work. One participant commented that the task and link analyses functions are directly useful with his work in optimizing work flow and ship layout of the GA his team were currently developing. Participants commented on the value of the 3D model making the conceptualization of the ship "*clearer*", increasing an understanding of the work environment and empathy with onboard crew. One participant noted "*you can almost pretend you are walking in the ship and everything becomes clearer*", giving a different perspective to the work spaces and layout. However, they detailed that 3D drawings lacked the simplicity of direct perspective and overview of 2D models, which are necessary for developing large, complex structures. It was noted that participants liked *E-SET's* function that allowed instantaneous switching between the 2D and 3D digital models to view the same information in different visual formats within one program.

In general, the participants were more pessimistic with integrating *E-SET* and ergonomics methods into "real-world" ship design projects. Several pointed out that it was *"not our main focus"*, stating that if they had "*time left over*" at the end of a project many things could be improved. Their focus as naval architects is to work towards the project's pre-established goals as efficiently and effectively as possible. Participants argued that although it is a *"nice thing to do"* they did not see a reason to go above and beyond the established governing requirements and customer requests. The perceived necessary time and financial investments added to the fundamental goals and design development of a project are seen to be unnecessary in a competitive marketplace where awarding tenders is heavily driven by economics. Thus, if the rules and regulations do not stipulate ergonomics support; customers do not specifically ask for it; engineering education curricula does not include it; and the management of naval architecture design firms do not support its implementation; the individuals and teams involved in ship design have no incentive to either learn or apply such knowledge into their work.

5.4.2. Integrating Ergonomics Tools into Software Solutions

Although participants found value in the ergonomics tools of *E-SET*, they were sceptical of the practical implementation of the software into their design work. During the focus groups participants discussed that the acceptance of *E-SET* would be more successful if the ergonomics tools applied to the 2D and 3D models were implemented within technical drawing software naval architects already use and are familiar with.

E-SET's 2D models are not the same format as typical 2D GA drawings or CAD programs used in ship design. They lack technical information and focus more on spaces and passageways within a ship. The participants were accustomed and trained to expect to derive technical data of equipment from 2D drawings. The original development direction chosen for *E-SET* was focused on revealing and mapping crew movement throughout a structure, *around* equipment and objects within a ship, rather than including detailed equipment specifications. Although the digital ship models themselves were poorly received, the response to the actual digital ergonomics tools and overall concept was positive. Ultimately, the participants wanted *E-SET's* functions, including the crew work task database, link analyses visualization and calculated output metrics integrated as an auxiliary function or application to a pre-existing technical design program. They felt this was the most pragmatic strategy for future development and integration into naval architecture work procedures.

Chapter 6

Discussion

This chapter extends the results presented in chapter 5 and discusses the implications of the findings by connecting it to other work performed and published within this research program, the greater scientific body of knowledge and the shipping industry. The chapter begins with section *6.1. Achieving Safety Through Design*, which provides a perspective of how the shipping industry relates ship design to maritime safety, ultimately providing the social context and motivation for the purpose of this thesis. This is followed by a discussion of how ergonomics applications can be developed and promoted within the shipping industry. The chapter concludes with a methodological discussion, an outlook on future research directions and recommendations to stakeholders.

6.1. Achieving Safety Through Design

The historical trend of shipping operations increasing safety and reliability can be largely attributed to advancements in safety regulations, ship design, shipbuilding knowledge and technologies. As the total tonnage transported globally by shipping has continually increased, accidents have dramatically reduced (Allianz Global Corporate & Specialty, 2012; 2015). However, major shipping accidents continue to occur, while occupational accidents onboard which result in crew fatalities and injuries persist (Norwegian Maritime Directorate, 2012).

As “safety” is a contextually dependent condition there are varying definitions, attitudes and perspectives for any situation (Cox, Tomás, Cheyne & Oliver, 1998; Praetorius & Lützhöft, 2012; Worrall, Orchansky, Masson, Nieto & Nebot, 2010). For shipping and naval architecture, a fundamental priority is to maintain safety by protecting the overall ship structure from damage or total loss (Chauvin, Le Bouar & Renault, 2008; Paine, 2013). A seaworthy structure protects the ship, its contents (e.g. machinery, cargo, passengers and crew) and surrounding environment (e.g. oil spills and environmental damage) (Lindøe, Engen & Olsen, 2011). As the design and construction of ships became safer, priority shifted towards increasing their operational efficiency. Contemporary naval architecture prioritizes powering, efficiency, stability, strength and seakeeping issues of a ship’s design first, after which the human element may be considered, and if so, only within the established design constraints (Andrews, Casarosa, Pawling, Galea, Deere & Lawrence, 2007). As a result, the safety, health and general priority of onboard crew has historically and contemporarily been of secondary focus and importance.

The physical design and layout of a ship influences crew behaviour and task execution (Forsell, Hagberg & Nilsson, 2007; Mallam & Lundh, 2016). As ships are large financial investments which generally stay in operation for several decades after being built (IMO, 2010), the lifecycle savings of “good” designs must be stressed, including positive contributions to productivity, safety and the economic bottom-line. There is little understanding, guidance or research on how to integrate ergonomics knowledge and user needs into the design of onboard workspaces and operations (Kataria, Praetorius, Schröder-

Hinrichs & Baldauf, 2015). This is reflected in the lack of mandatory international regulatory support (IMO, 2009; Mallam & Lundh, 2013), naval architecture priorities (Andrews, Casarosa, Pawling, Galea, Deere & Lawrence, 2007; Mallam, Lundh & MacKinnon, 2017a) and lack of usable shipping-specific ergonomics tools and methods for ship design and construction processes (Mallam, 2014).

6.2. Developing Ergonomics Applications in the Shipping Industry

6.2.1. The Role of Education & Knowledge Mobilization for Social Change

Increasing ergonomics knowledge in the shipping industry and amongst its stakeholders is a fundamental goal of this thesis and its appended articles. The diversity of stakeholder competencies and experience is an asset only if knowledge can be effectively mobilized and utilized by multidisciplinary teams (McDermott & O'Dell, 2001). The proposed integration strategy based on the research from appended articles I and II, and the development and testing of design-driven participatory methods and digital solutions detailed in appended articles III and IV is to facilitate ergonomics knowledge mobilization in ship design and construction processes. The utilization of these methods and solutions in the shipping industry can only be successfully achieved through increasing stakeholder awareness of the added value that ergonomics can contribute to the industry. Thus, educating the shipping industry and its stakeholders is an essential requirement; and of particular interest to the scope of this thesis are naval architects and their work practices. Ergonomics is generally not emphasized in the formal education, standard professional work procedures, methodologies or in the rules or regulations that guide naval architecture. Designers are taught to follow and optimize project specifications based on customer specifications and limitations within the constraints of the rules and regulations of a particular industry (de Vries, Costa, Hogström & Mallam, 2015; Wulff, Westgaard & Rasmussen, 1999a). This creates technical and economic focused engineering and project management processes.

Article IV explored naval architecture student perceptions of both *E-SET* and ergonomics applications in conceptual ship design. The participants reported perceived benefits from using *E-SET* and in theory were generally positive of the purpose of ergonomics and participatory design applications. However, even as students, the participants had negative opinions regarding the practical implementation of ergonomics into engineering projects, perceiving it as counterintuitive to basic engineering project management goals - adding additional resources, costs and time to a project's scope. These findings reveal a fundamental lack of understanding and knowledge in young engineering students regarding ergonomics and its role within engineering and design. This can be viewed as a reflection of the education that the students received and influence from the greater culture of the shipping industry, engineering and naval architecture disciplines. Ultimately, user perceptions and attitudes are influenced by the culture they live and work within. This directly affects the adoption of new technology and methodologies (Schepers & Wetzels, 2007).

The failure to integrate ergonomics into system design is not a failure of the technical system as much as it is a failure to accommodate its social sub-systems (Nadin, Waterson & Parker, 2001; Neumann, Ekman & Winkel, 2009). Knowledge is a systemic, socially constructed, context-specific representation of reality, and thus is not an object to be transferred, but a by-product of interactions between individuals within a social system (Parent, Roy & St-Jacques, 2007). According to the Dynamic Knowledge Transfer Capacity model proposed by Parent, Roy & St-Jacques (2007), in order for knowledge transfer to be successful a system needs to possess or acquire four capacities: central to the model is the ability to (i) generate, (ii) disseminate and (iii) absorb knowledge, while a second order function is that knowledge transfer activities are (iv) adaptive and responsive. This thesis's research has generated knowledge (e.g. ergonomics integration strategy for ship design and the development of *E-SET*) and attempted to develop and test solutions that facilitate the disseminative capacities of ergonomics knowledge into naval architecture. This research has strived to adapt and respond to ship design methodologies, naval architecture work procedures and tools, in order to facilitate absorptive capacities through pragmatic ergonomics solutions. However, ultimately cultural challenges can be the main obstacle for knowledge absorption (Parent, Roy & St-Jacques, 2007). As the results of article IV reveal, a poor absorptive capacity was highlighted by discussions amongst participants whom detailed negative perceptions of ergonomics in practice and a general resistance to change.

Increasing ergonomics knowledge and skills within engineering education curricula is critical for evolving the perception and utilization of ergonomics by engineering disciplines (Vicente, 2006; Wulff, Westgaard & Rasmussen, 1999b). Buch & Bucciarelli (2015) argue that to provide a more contextualized approach engineering education should be expanded by supplementing the typical technical curricula, emphasizing reductionist problem-solving, with elements of the humanities and social sciences. Engineering students who took an ergonomics course as part of their curriculum were found to be first challenged by the new learning style, but reported increased knowledge and understanding of the purpose and benefits of developing products and systems for users (Berglund, Andersson, Hedbrant, Pavlasevic & Stålhand, 2015). The results from article IV reveal similar findings, where participants described increased empathy for onboard crew after visualizing and exploring the ships physical work environment and crew movement patterns in *E-SET*'s 3D models. These findings suggest that integrating design-specific ergonomics issues and crew work demands through visualization is a valuable addition to naval architecture education and ship design methods, mediating knowledge gaps between users, ergonomists and engineers.

6.2.2. The Role of Technology in Facilitating Participatory Processes

The real-world application of participatory practices within design projects must be practical and usable (Holone & Herstad, 2013). Due to the highly distributed, multidisciplinary nature of the shipping industry a pragmatic and sustainable integration strategy requires a distributed approach to participatory design and ergonomics applications.

Developing a ship design can generally vary between 6-18 months and building between 6-24 months (van Dokkum, 2011). It is impractical to embed seafarers and ergonomists in the varying geographical locations and over periods which can span several years from the start to end dates. Traditionally, seafarers would spend time at a shipyard during the building period of a structure in order to provide input as SMEs, however, this has become rare in contemporary manufacturing processes (Earthy & Sherwood Jones, 2010; Grech & Lemon, 2015). Chauvin, Le Bouar & Renault (2008) found it difficult to gather all the required stakeholders together for meetings in person at appropriate periods throughout the long and variable timelines of ship development. Relatively rapid decisions and parallel work are required in order to keep project schedules on time, compromising in-person participatory decision-making processes. Furthermore, employee engagement levels within the shipping industry are typically lower than shore-based industries as crew are an inherently transient sample who are difficult to reach (Bhattacharya, 2015; Hetherington, Flin & Mearns, 2006).

With stakeholders spread across geographically-distributed locations communication and knowledge sharing can be a challenge (Coar, 2004). In order to facilitate early and continuous user input and ergonomics evaluations throughout ship development, computer-based solutions are a logical solution to bridge communication gaps and facilitate participatory design processes. Stakeholders require appropriate tools and techniques that facilitate effective communication and knowledge mobilization for participatory project environments to succeed (Sanders & Stappers, 2008). Closing the gaps between geographically-distributed, multidisciplinary stakeholders requires two initial fulfilments: (i) common boundary object(s) that all stakeholders can relate to and communicate through, and (ii) have the boundary object(s) web-based with distributed information sharing and project coordination capabilities. Furthermore, in order for the technological solution itself to be adopted and embedded within the shipping industry it must be perceived by the industry and its stakeholders to be useful, usable and ultimately add value to design and construction processes.

6.2.2.1. The Common Denominator: Participation Through GA Drawings

To facilitate understanding, communication and joint problem-solving environments amongst stakeholders, boundary objects (such as GA drawings) can establish tangible means for individuals to share and represent their knowledge (Carlile, 2002; 2004). Several early publications of the author’s Doctoral research program suggested that the most tangible, shared and understood “object” which intersects the diverse stakeholders involved in ship development are GA ship drawings (Lundh, Paraïso & Mallam, 2013; Mallam & Lundh, 2014). Original GA drawings were used to create physical mock-ups (cardboard and paper) to facilitate participatory design data collections with users (see Figure 15). The drawings themselves are a common platform for which a participatory design approach can be structured around, creating a common language and understanding between multidisciplinary stakeholders (Broberg, Andersen & Seim, 2011). Naval architects conceptualize and develop GA drawings; shipyards use GA drawings to construct structures; governing bodies, classification societies and ergonomists use GA drawings to inspect and evaluate design and construction criteria; and crew (particularly engine crew) use GA drawings as an integral part of their work, from structural familiarisation to operational and maintenance procedures.

Mapping of user movements and tasks visualized through boundary objects such as physical mock-ups and models (e.g. full-scale 1:1, scaled 1:8, 1:16, LEGO pieces, etc.), 2D and 3D CAD drawings and 2D paper drawings and sketching can enhance ergonomics evaluations throughout the design process (Anderson & Broberg, 2015; 2016; Aromaa & Väänänen, 2016; Mallam, Lundh & MacKinnon, 2015b; Österman, Berlin & Bligård, 2016). This is particularly advantageous during early GA design drafts where basic physical dimensions are developed, and crew logistics and space requirements can be optimized early and economically in the overall process. Article I explored how 2D pencil-and-paper GA ship drawings and sketching could be used with crew to communicate their work practices and demands to non-experts. This was further explored in article II with a case study of an operational ship at sea. This study investigated the accuracy of GA drawings for ergonomics evaluations and how crew related to these objects. The research findings from articles I and II influenced and contributed to the development of a technology (i.e. *E-SET*) aimed to facilitate participatory design processes and knowledge sharing throughout ship development which is detailed in article III and tested in article IV.

Figure 15. A ship’s crewmember working with a cardboard mock-up.

6.2.2.2. Early Ship Design Ergonomics Integration Solution

In the competitive industry of shipping and lean manufacturing, ergonomics applications must be strategic and pragmatic. Article III details the integration strategy, motivation and purpose of the software prototype, *E-SET*, founded upon two basic ergonomics design principles:

(1) early and continuous integration of ergonomics throughout design and construction;

(2) facilitate participatory ship design processes by increasing knowledge transfer specifically between three key, distributed stakeholder groups: users (i.e. ship crew) designers (i.e. naval architects), ergonomists.

These two principles are addressed by a pragmatic design philosophy and technology focused on mobilizing ergonomics knowledge between key stakeholders. These three identified stakeholder groups must be directly involved throughout the project, encouraging shared ownership of design development. Articles III and IV describe a platform where multidisciplinary, distributed stakeholders share a “common ground” and tacit knowledge can be codified and transferred between professional disciplines and geographical areas.

Most ships are unique structures and built for specific purposes, with varying work environment designs, layouts, operational systems, equipment and installation characteristics (Hetherington, Flin & Mearns, 2006; Stopford, 2009). Thus, issues of fidelity (high versus low) and 2D versus 3D visualizations were weighed against practical considerations regarding the software’s potential visualization properties. 2D representation of a ship’s deck layout are an industry standard for GAs, however 3D ship models of the work environment require additional resources to both create and alter as ship designs develop with increasingly greater detail. Higher fidelity models generally allow the identification of more usability problems (Boothe, Strawderman & Hosea, 2013), and while users favour high fidelity graphics (Perez & Neumann, 2015) they require increased computational resources to implement.

Alternatively, low and medium fidelity allow for relatively fast and easy ergonomics interventions early in the design process (Hallbeck, Bosch, van Rhijn, Krause, de Looze & Vink, 2010).

Ship design cycles are highly iterative and the construction (e.g. fitting of the superstructure) of a ship can begin before detailed drawings are finalized (Chauvin, Le Bouar & Renault, 2008). Thus, creating customized, accurate representations of a future ship's work environment with high fidelity 2D and 3D digital renderings is difficult, if not impossible to efficiently maintain throughout iterative ship design cycles. Similarly, detailed multidisciplinary evaluations of the work environment or site-specific task analyses may not be not practical, as each make and model of equipment and installation configuration is highly variable (e.g. design of boilers from company A versus company B have different overall dimensions, design characteristics, sensors, interfaces, etc.).

Creating a virtual environment for early participatory design evaluation requires a flexible and pragmatic solution (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012). Thus, a low-to-medium 3D fidelity was chosen for *E-SET's* ship models and run on a flexible gaming software platform (see Figure 16). Article IV suggests that the naval architecture students found benefit in utilizing 3D environments. Results indicate that 3D visualization of the ship's layout and work environment increased their empathy towards the users and their onboard work.

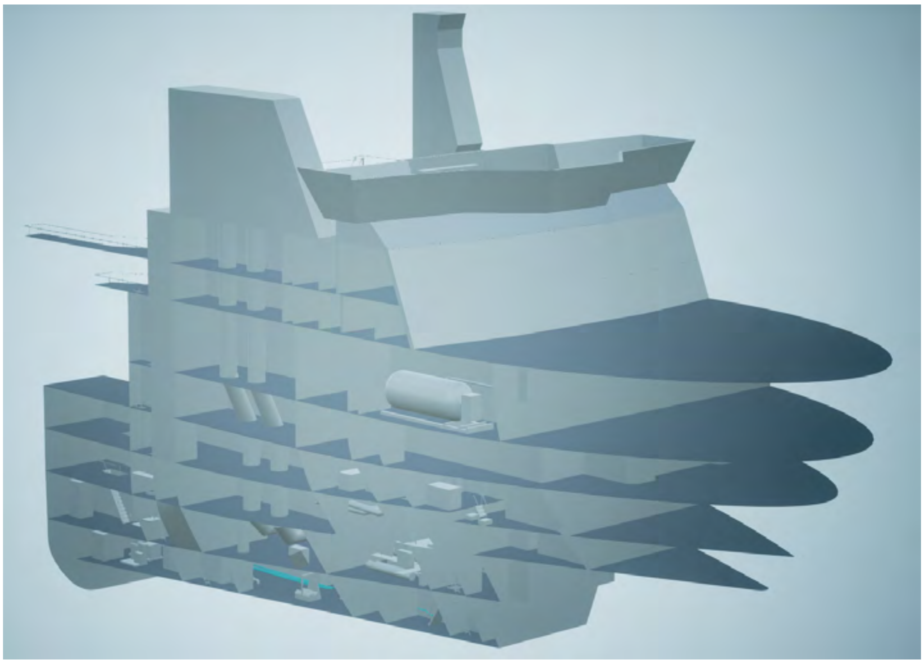

Figure 16. Screenshot of a global view of a ship's superstructure in 3D mode.

6.2.2.3. E-SET's Functions: Inspiration from Web-Mapping Services

E-SET's functions are focused on what, where and how crew perform tasks onboard a ship. Two methods were used as the foundation for *E-SET*: task and link analyses. Establishing a catalogue of crew work tasks through extensive task analyses provides the fundamental information of onboard crew demands and user-centred design. This can then be visualized and mapped on a ship's GA drawings through link analyses. The task and link analyses combination provides naval architects and stakeholders with tangible, quantifiable information and visual feedback for direct implementation into design work.

E-SET applies the same concept and functions to physical work environment and movement analyses as web mapping services (Mallam, Lundh & MacKinnon, 2017b). For example, Google Maps provides route information for varying modes of transportation (car, public transport, walking), including distances, average travel time, disruptions (i.e. traffic or construction) and alternative routing in 2D, as well as a street view 3D mode (see Figure 17).

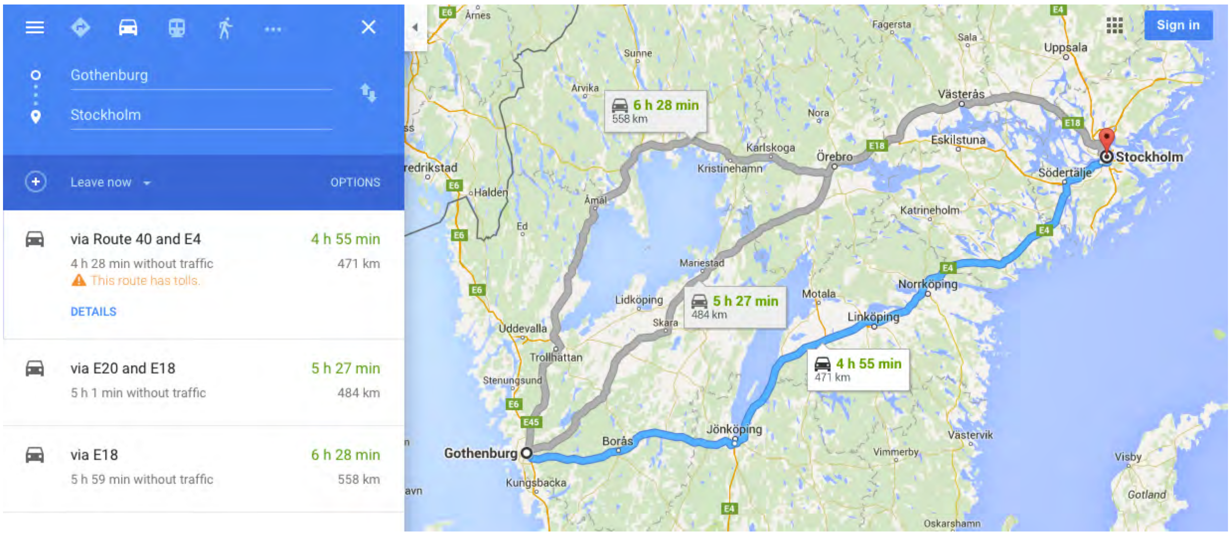

Figure 17. Google Maps 2D route planning & analysis.

This same type of information is relevant for onboard crew (particularly engine crew) in their personal movement throughout a structure, as well as the logistics of heavy and/or awkward equipment and stores. *E-SET* has a database of crew work tasks and movement linkages which can be customized and expanded by SMEs for a particular ship or project scope. Tasks may represent spatial connections between two linkages (e.g. ship's bridge to/from lifeboats) or connections requiring multiple linkages (e.g. changing a piston on the main engine – movement to/from/within the engine department by crew). *E-SET's* output metrics include: distance between nodes (total and segment), walking time (derived from standardized walking speed: 1.40 m/s), total number of stairways walked up/down, total number of doorways and defined obstacles passed (see Table 2).

Table 2. Example of output metrics calculated and for a single work task.

Task 021	
Distance (Total)	105 m
Walking Time	1 min 15 s
Doors Passed	4
Stairs Going Up	6
Stairs Going Down	0
Obstacles Passed	1

The quantitative data can then be visualized through 2D GA drawings into relatively low fidelity 3D environments which outline basic structural dimensions and major equipment characteristics (see Figure 18). This creates an opportunity for workspace evaluation and participatory input from both a 2D and 3D perspective. Overlaying multiple tasks within the same drawing can reveal high traffic areas and critical passageways for crew throughout a structure. Integrating these metrics into the participatory process can help stakeholders identify key areas of interest. Crew can provide contextual input and practical advice for how specific design choices impact onboard operations, and together with naval architects develop optimized solutions.

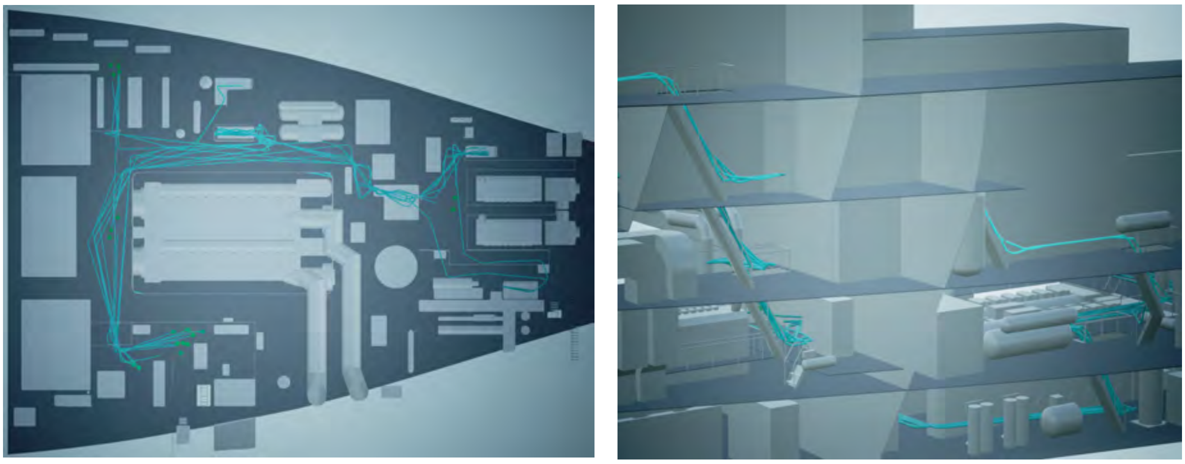

Figure 18. Movement of 20 unique crew work tasks mapped throughout a ship's engine department in 2D mode (left) and 3D mode (right).

Visualization programs, such as *E-SET*, have a variety of usages apart from explicit project design and development applications. This includes use as an education and training tool for both naval architects and crew, as well as direct industry applications once a structure is put into operation (e.g. for new crew familiarisation and planning of operational, maintenance and logistical procedures onboard) (Lundh, Mallam, Smith, Veitch, Billard, Patterson & MacKinnon, 2012; Stone, Caird-Daley & Bessell, 2010).

Ultimately, attempts to integrate ergonomics and participatory design practices into the traditionally engineering intensive practice of ship development must overcome fundamental challenges. This requires effective and efficient mobilization and management of knowledge between geographically-distributed, multidisciplinary stakeholders that ultimately facilitates the development of tangible, value-added design solutions via practical, resource efficient practices.

6.2.3. The Role of Regulatory Bodies

Shipping's long and internationalized history has influenced how the governance of the industry has evolved and exists in present day. International maritime law has an array of conditions which financial stakeholders can exploit to help reduce costs, and thus maximize profits within the extremely competitive industry. Registering ships with "flags of convenience" and "open registries" are popular practices for lowering regulatory costs, labour rights and wage levels (Progoulaki & Roe, 2011). Over the past several decades there has been an increase of international ship management and crewing companies, with ship owners increasingly locating to third world countries (Bloor, Thomas & Lane, 2000; United Nations, 2014). More than 65% of the global fleet is manned by multi-national crews, with 10% of the fleet manned by crews consisting five or more nationalities (Bloor, Thomas & Lane, 2000;

Kahveci, Lane & Sampson, 2002; Progoulaki & Roe, 2011). Although automation has led to reduced manning levels onboard ships, longer working hours are required of smaller crew compliments (Bloor, Thomas & Lane, 2000; Kahveci, Lane & Sampson, 2002; Progoulaki & Roe, 2011).

Minimum standards for ship design and construction are highly structured and enforced. As regulations guide naval architecture work processes, adhering to the regulatory frameworks (e.g. SOLAS Convention) will produce a satisfactory design and adequate “safety”, as defined by the IMO (de Vries, Costa, Hogström & Mallam, 2015). This issue relates to the shipping industry’s concept of safety discussed in section *6.1. Achieving Safety Through Design*: naval architecture predominately focuses on the safety, seaworthiness and technical elements of a ship structure, with secondary consideration to the crew, work environment and onboard operations within the structure. Expanding design regulations to incorporate ergonomics issues faces a paradoxical situation: ergonomics will be validated and applied by naval architects in design if present in the regulations, however, ergonomics requires the shipping industry’s support (including naval architecture’s) to influence amendments in mandatory rules and regulations.

It has been nearly twenty years since the IMO first drafted a resolution establishing their human element vision, principles and goals (IMO, 1997). Although subsequent documents and resolutions have been developed (e.g. IMO, 1998; 2004; 2006a, 2006b, 2006c) they remain fuzzy and non-mandatory (Mallam & Lundh, 2013). Several early publications connected to the author’s Doctoral research program discuss the necessity of establishing mandatory regulatory support in order for ergonomics applications in shipping to be adopted and successful (e.g. Mallam, Smith & Lundh, 2012; Mallam & Lundh, 2013; Mallam & Lundh, 2016). Although mandatory regulations are important for widespread ergonomics adoption in shipping, the author’s perspectives have evolved since those early publications (Mallam, Lundh & MacKinnon, 2016). From a pessimistic perspective, regulatory bodies such as the IMO are large, bureaucratic and slow-adapting organizations. Developing regulations on an international level is a highly politicized process controlled and influenced by an array of international entities with differing agendas. Rather than trying to “push” ergonomics into the system through regulations, it is the perspective of the author that a more effective pursuit is a bottom-up initiative.

A successful bottom-up approach in promoting ergonomics utilization in shipping is dependent on one issue - demonstrating that ergonomics saves money. If implementing ergonomics in ship design and construction is truly beneficial to the financial stakeholders (i.e. money is saved through increased productivity, reduction in accidents or a combination of a variety of factors), then industry will embrace proven ergonomics solutions whether or not they are supported by regulatory bodies. Although top-down pressure must remain on regulatory bodies to formally adopt ergonomics frameworks, rather than “forcing” ergonomics into shipping practices by regulation, a bottom-up initiative can facilitate the development of a naturally evolving and adapting process. A bottom-up approach requires practical evidence-based applications which stem from building relationships with industry partners (e.g. design firms, shipyards, operators, etc.) who are willing to investigate these issues further and support longitudinal, holistic research studies in shipping. A bottom-up approach allows for ergonomics applications in shipping to develop and refine pragmatic methodologies and technical solutions in an environment where ergonomics innovation, efficacy and efficiency develops organically through practice.

6.2.4. The Role of Design Standardization

Ship designs are generally highly customized structures with great variance of onboard work environment and equipment characteristics (Hetherington, Flin & Mearns, 2006; Stopford, 2009). Seafarers typically work on a contractual basis and may frequently change ships, co-workers and companies (Bhattacharya, 2015). Thus, the physical and organizational environments they work within are highly variable. The constant requirement for crew to relearn new interfaces, work environments and procedures makes them feel undertrained (Allen, 2009), while a lack of ship-specific knowledge is a frequent contributor to maritime accidents (Rothblum, 2000).

Contrasting the shipping industry with commercial aviation, arguably the most globally standardized transport industry, reveals fundamental differences regarding design and construction practices. A Boeing 747-400 or Airbus A320 aircraft have similar, if not identical characteristics to all other namesakes constructed. A pilot trained for a specific type of aircraft should have the competence for successful operation regardless of the airline. Conversely, a seafarer, even with proper education and certification, does not necessary share the same circumstances. Although it is routine for seafarers to switch between ships, their knowledge and understanding of a particular ship's characteristics and operational nuances must be developed through experience and time served working onboard. Thus, their tacit knowledge acquired over time working on a particular ship with its specific systems, design configurations and experienced crew are a valuable asset, but unfortunately is often lost or only partially developed due to crew turnover.

Ship designs are highly unique because their purposes are greatly varied. From a design perspective ships are optimized for maximizing efficiency by increasing cargo space, and minimizing procurement and operational costs. Ship design specifications depend on a wide variety of variables, such as cargo type (e.g. requires double hull, onboard cranes, speciality refrigeration or insulation, etc.); port characteristics (e.g. size, depth, equipment, local laws, etc.); planned routes and operating conditions (e.g. ice class, trans-oceans, max size for canal/lock passages, etc.); flexibility in operations (e.g. in case of market fluctuations can a ship intended to transport commodity A to country X be retrofitted to now transport commodity B to country Y?); manning levels (e.g. operational requirements, safety equipment, accommodations, etc. for a crew of 10 versus 20); and resale value. However, as ships are built, bought and sold as investments a ship may have several owners or operators over its life, as well as differing operational purposes, procedures and trade routes (Grech & Lemon, 2015).

Full standardization to the extent that exists in commercial aviation may not be achievable or desirable for merchant shipping. However, a move towards partial standardization of design is a pragmatic solution which would have benefits for both procurement and operations. The results from articles I and II found that crew desire operational flexibility in the design of a ship and its work environment. Especially critical for engine crew is that they are able to move safely and efficiently throughout a structure. This requires clear routes and easy access to/from different areas and equipment onboard a ship.

Partial standardization of a ship, work environment, and equipment design and layout ensures there are standardized elements, regardless of the ship. Partial standardization also prevents overtly inhibiting naval architecture innovation or design customization. This may be achieved through a variety of methods such as goal-based design standards from regulatory bodies (e.g. Lützhöft & Lundh, 2009; Mallam & Lundh, 2013; Mallam, Lundh & Smith,

2012) or naval architecture firms, equipment manufacturers and shipyards offering standardized options (or more modular methods offering various standardized options). Regardless of how partial standardization is implemented it offers a potential solution for facilitating user-centred design in new ship development and crew familiarization in shipping operations. This is an area which should be investigated in greater detail.

6.2.5. The Role of Ergonomics

Ergonomics is a design-driven, action-orientated discipline (Dul, Bruder, Buckle, Carayon, Falzon, Marras, Wilson & van der Doelen, 2012). However, ergonomics as a discipline has not been completely successful in influencing and integrating into engineering or shipping domains. According to Meister (1999), engineers were the major contributors to ergonomics practices prior to World War I. This may have directed ergonomics into a branch of engineering, had military-based cognitive scientists not adopted "human factors" in design and research during the first half of the twentieth century (Meister, 1999).

Ergonomics methods and tools have a tendency to be used by other domains if they appear accessible and originally developed from engineering methods (Stanton & Young, 2003). They should communicate, quantify and document ergonomics aspects of design (Village, Greig, Zolfaghari, Salustri & Neumann, 2014). Article IV found that the participants reported value in the ergonomics functions of *E-SET,* but wanted them to be integrated into the CAD programs they were familiar with and used for technical ship design. This is likely to facilitate the designer's acceptance and utilization of ergonomics methods (Gomes de Sá & Zachmann, 1999), but has implications for how ergonomics is applied and integrated into the ship development process. Although complete integration of the ergonomics functions into the engineering-specific CAD programs would likely encourage and facilitate increased usage by naval architects, it does not guarantee that it will be utilized. Furthermore, increased integration reorganizes power back to the designers and compromises the structure of the participatory design process, alienating those not trained to use specific and highly technical engineering software.

A balance must be struck between further integrating ergonomics tools into CAD programs with establishing and maintaining a participatory design process where users and ergonomists are utilized within a project. Engineering design is a social process of negotiation between differing interests and idealized project management promotes the free exchange of ideas and knowledge between different stakeholders (Theberge & Neumann, 2013; Wulff, Westgaard & Rasmussen, 1999b). If software programs such as *E-SET,* and/or its imbedded functions are to be integrated into technical CAD design programs, then the ergonomics integration strategy for ship design would have to adapt and evolve to ensure a platform is still available which facilitates multidisciplinary communication and participatory design processes.

6.3. Methodological Discussion

6.3.1. Reflections on the Methodological Approach

Reading the four appended articles in sequential order conveys how the author's Doctoral research program progressed by building directly from its prior findings: beginning first with two initial exploratory data collections (articles I and II), which informed the development of the software prototype, *E-SET* (article III), and ended with the testing of *E-SET* with intended users (article IV). Due to the exploratory research questions, a predominantly qualitative research approach was implemented. As a result, the findings may lack generalizability, but can make valuable contributions to theory (Silverman, 2013). Findings were derived through several data collections that implemented different types and combinations of qualitative and quantitative methods. Although the findings have yet to be applied or tested during real ship design and construction, they provide a theoretical framework as a foundation for future academic and industry developments.

6.3.2. Data Collection

There is no single best way to choose and implement an ergonomics program (van Eerd, Cole, Irvin, Mahood, Keown, Theberge, Village, St Vincent & Cullen, 2010) or choose design methods (Hall, 2001). This is particularly true for the specific scope of creating an ergonomics design framework for naval architecture design procedures, where little research or application has been performed. To investigate the research questions a range of methods were utilized in both field and laboratory data collections to explore, analyse and further develop fundamental issues regarding the research scope.

This thesis includes three data collection approaches, implementing the following methods: focus groups (articles I, II and IV), field data collection, interviews and naturalistic observation (article II) and usability testing questionnaires (article IV). By employing several different types of data collections and methodologies the cumulative view triangulates where different data intersects, providing a “true” picture of a situation (Silverman, 2013). Triangulation increases validity of research findings as conclusions are built from multiple, varying forms of evidence and data points (Creswell & Miller, 2000).

6.3.2.1. Sample Characteristics

Ship procurement processes include a vast number of individuals and organizations. As the scope of this thesis is design-driven, only the primary stakeholder groups most important for system analysis and idea generation of an ergonomics process were focused on: employees (i.e. seafarers), designers (i.e. naval architects) and ergonomists (i.e. the researchers) (Vink, Imada & Zink, 2008). The research participants for articles I and II were seafarers, and article IV were naval architecture students. Limiting the scope to these two stakeholder groups was purposeful in order to focus on the design methods and tools, rather than the extended network of stakeholders and external conditions. Although beneficial from an experimental research perspective, adapting the research findings to real-world ship design and construction projects may expose weaknesses and limitations in the research’s findings and applications.

The participant samples for each data collection were relatively small (article I: 9 participants; article II: 6 participants; article IV: 13 participants) due to the specialization of the research questions, limited number of potential participants to draw from and limited research resources available. However, as the research scope and participant qualifications were highly specific, smaller sample sizes still provided rich data to draw conclusions from in both the exploratory focus groups and usability testing data collections. Smaller focus groups can actually be advantageous for specialized topics, increasing the likelihood of all individual participants contributing and creating an environment for greater interaction and deeper discussions (Carey, 1994; Krueger & Casey, 2009). Similarly, although there is no adequate sample size recommended for usability testing (Lewis, 2006), most usability problems are detected within the first 3-5 subjects, while subsequent testing delivers diminishing returns where additional subjects are unlikely to reveal new information (Lewis, 1994; 2006; Nielsen & Landauer, 1993; Virzi, 1992). As the targeted participant populations are highly specialized professionals who are difficult to access and recruit (Hetherington, Flin & Mearns, 2006), each specific data collection and its methods were chosen with prior knowledge of the potential participant recruitment pool and possible constraints. A conscientious effort was made in the planning and execution of each data collection to adhere to best methodological practices in order to obtain sufficient sample sizes and data saturation.

6.3.3. Data Analysis

6.3.3.1. Grounded Theory

Grounded Theory was utilized in the analysis of the focus group, interview and observational data collections of articles I, II and IV. As each data collection was exploratory in nature a Grounded Theory framework facilitated the identification of emerging themes from the collected data (Corbin & Strauss, 2015; Patton, 2002). Ground Theory helped identify and categorize core concepts from the transcribed participant data and relate them to the overall research questions and purpose of the appended articles.

As the author planned the data collections, conducted the interviews, transcribed and analysed the data, the biases of the researcher can pose a threat to the Grounded Theory Analysis (Corbin & Strauss, 2015; Thomas & James, 2006). The greatest effort was made by the researchers to acknowledge biases and account for them in the data collection and analysis processes. According to Dey (1999) prior knowledge and experience can be an asset for Grounded Theory analysis as long as it *informs* analyses rather than *direct* it.

6.3.3.2. Field & Model Measurements

Apart from the interviews and naturalistic observation analysed by Grounded Theory, the data collection detailed in article II also investigated the physical ship structure. Quantitative measurements of the onboard built environment were compared against the ship's GA drawings from which it was built. This involved the collection, analysis and comparison of the dimensions and distances between various work areas, passageways and crew "link" combinations throughout the ship. Field measurements were performed with a combination of traditional measuring tapes and laser distance meters, while the 2D GA scaled drawings were analysed through both paper (by ruler) and digital (CAD drawings) formats.

The distance measurements reported from both the field and scaled models may be imprecise and unreliable due a variety of factors, including the measurement equipment utilized, variability in measurement conditions and protocol implemented. In particular, during the field data collection the researcher found it inaccurate and unmanageable to track crew movement patterns throughout the ship structure (i.e. large distances over multiple deck levels) with the available measurement tools. However, what emerged as the key finding did not directly relate or rely on precise distance measurements, but rather the accuracy of equipment and piping (and to a lesser degree, electrical) installation placements and passageway dimensions. These measurements were generally easier to collect accurately due to their relatively smaller dimensions and distances, and ultimately contributed more important findings for how conceptual GA drawings could be utilized for ergonomics analyses.

6.3.3.3. Usability Questionnaire

The mixed-methods usability testing outlined in article IV implemented focus groups, as well as the standardized usability questionnaire, PSSUQ. As the PSSUQ administered on its own is suggested to have a sample size of ninety or more individuals (Lewis, 1995), a mixed-methods usability testing framework was designed in order to strengthen the reliability and validity of findings, while still adequately identifying usability problems (Lewis, 2006). The PSSUQ was chosen over other popular, well-established usability questionnaires because its measures (system usability, usefulness, information quality and interface quality) best fit the research questions and development stage of *E-SET* at that time period.

The PSSUQ can also track changes in usability as a function of the design changes made throughout development for both within a version, as well as across different versions (Lewis, 2002). This is an important quality because the best reference for generalizing usability results is one's own data that is derived from similar evaluations with similar products, tasks and users (Sauro & Lewis, 2012). Due to the novelty of the *E-SET* prototype, specialized target audience and exploratory nature of the mixed-methods usability framework, pairing the PSSUQ with a follow-up focus group provided a standardized, quantitative foundation which can be used to track future iteration developments, with more in-depth descriptive qualitative participant data.

6.4. Moving Forward: Recommendations for Future Research & Stakeholders

Both the proposed future research recommendations and recommendations to stakeholder's have a fundamental shared aim: improve ship design solutions through participatory practices. This thesis argues that improved design can be achieved by increasing ergonomics and crew knowledge mobilization in ship design and construction processes. Although the scope of this thesis has been on shipping, much of the future research and stakeholder recommendations are relevant to other industries, and the ergonomics discipline as a whole.

6.4.1. Future Research

The integration strategies and solutions presented within this thesis are theoretical, and primarily focused on ship users (crew) and ship designers (naval architects). In order to further progress and apply this thesis's findings, future research must investigate and integrate into real-world ship procurement projects. This requires joint partnerships and collaboration between academia and industry stakeholders involved in conceptual design and/or construction, including, but not limited to, naval architecture firms, shipping companies, financers, shipyards, equipment manufacturers, construction contractors, sub-contractors and regulators. The application of ergonomics within engineering projects allows for the testing and validation of theoretical methods and solutions under real-world conditions, thus facilitating their pragmatic development and improvement through practice.

Future research must further investigate when, where and how ergonomics and seafarers can contribute to improved ship design, including what solutions best bridge the knowledge gap between multidisciplinary, geographically-distributed stakeholder networks in engineering projects. This includes further examination into how the functions of *E-SET* should be integrated into naval architecture work procedures and technical design programs. Future research should focus not only on design methods and tools (such as those presented within this thesis) which are used to develop ship designs, but also on the construction process. A better understanding of the transition between conceptual design and the finalized constructed ship structure and work environment is required. Thus, extending this thesis's findings to investigate how GA drawings and specifications lists are utilized by shipyards throughout construction, and how ergonomics applications can be implemented on-site throughout construction at shipyards is a valuable pursuit.

Of interest to the ergonomics discipline, including its application in shipping, is to better understand the knowledge levels and attitudes of engineers (including naval architects) towards ergonomics and its applications in engineering projects. This would help the ergonomics discipline to identify opportunities and threats of ergonomics applications in engineering pedagogy and practice, informing strategies to optimize ergonomics pragmatic utility.

This thesis, its recommendations, and the ergonomics discipline in general, is dependent upon economics. Demonstrating the economic benefits of ergonomics applications in engineering projects is critical to its adoption by the shipping industry. This is a fundamental requirement for widespread implementation of ergonomics applications in real-world projects. Without an economic understanding of the impact of ergonomics its utility will continue to be questioned by project stakeholders, and thus underused or completely ignored by engineering disciplines and the shipping industry.

6.4.2. Recommendations to Stakeholders

- Ergonomics must be incorporated more into the formal curricula of undergraduate and graduate engineering programs. Ergonomics, like other engineering skills, requires a foundation of knowledge and understanding for future generations of engineers and designers to build upon. Without formalized ergonomics education within engineering curricula ergonomics will continue to be underutilized and misunderstood.
    - Shipping stakeholders, but particularly naval architects, should spend an extended period of time onboard a ship, or ships, at sea (whether during their education and/or periodically throughout their career for professional development). This would provide naval architects with first-hand experience and context for the demands of working at sea from the user's perspective during operation.

- Shipping industry stakeholders should be open to undertake pilot studies investigating ergonomics and participatory applications in ship design, construction and operations. Although the economic, safety and productivity benefits in shipping generally lack empirical evidence, the theoretical contributions and benefits, including the content found within this thesis, should motivate further examination into the practical implementation of ergonomics. The shipping industry requires a champion to investigate further ergonomics applications and methods.

- Ergonomics applications in ship design and construction must be pragmatic and aim to integrate within naval architecture design procedures and tools. This principle motivated all work performed within this thesis and is critical to facilitate applied ergonomics integration.

- GA drawings and design sketching are practical, commonly shared objects which naval architects and crew can use to communicate. This shared platform is already developed through traditional ship design and can be utilized for translating tacit crew knowledge and experience into tangible design solutions. Crew knowledge acts as a design validator, providing direct motivation for or against design solutions by contextualizing work demands and demonstrated to naval architects through GA drawings, visualization and storytelling.

- Regulators such as the IMO should continue to formalize ergonomics within international shipping. As seafarer competency requirements have advanced a disconnect has emerged between training and operational criteria (STCW) and ship design criteria (SOLAS), where design regulations currently fail to support operational regulations (Mallam & Lundh, 2013). The development of mandatory, goal-based design standards can help guide shipbuilding and improve the quality of work environments and ship designs for onboard crew.

Chapter 7

Conclusions

This thesis has investigated the pragmatic implementation of a participatory design framework for ship design and construction processes. It has focused on transforming ergonomics knowledge and tacit crew experience into tangible design support and solutions in naval architecture. This research has aimed to bridge the gap between multidisciplinary, geographically-distributed stakeholders involved in large-scale engineering projects.

Major findings from this thesis are:

- Before ergonomics is to make a meaningful, widespread impact within shipping the attitudes and cultural norms of the industry must evolve as a precondition for knowledge transfer to successfully occur. Integrating ergonomics into ship design and construction is particularly valuable for the shipping industry because merchant ships require large financial investments and generally have relatively long operational lifecycles (25+ years). Thus, creating an onboard work environment which promotes safety and productivity through user-centred design solutions has positive implications throughout a ships operation, not only for crew, but other connected stakeholders as well.

- This thesis investigated a bottom-up initiative through the development of pragmatic methodologies and tools specifically aimed at naval architects and the design process. However, for the shipping industry to successfully adopt ergonomics a holistic systems perspective must be taken with buy-in from stakeholders such as ship financers, owners, operators, shipyards, legislators, insurance companies and classification societies. Ultimately, this requires education and for ergonomics to possess the generative, disseminative, absorptive, adaptive and responsive capacities required for successful knowledge transfer in shipping and new ship development.

- Combining increased ergonomics education with the development of usable ergonomics tools which are further integrated into engineering software can support naval architects to implement ergonomics applications, potentially making them the champions of ergonomics in ship design. However, this strategy may alienate seafarers, ergonomists and other project stakeholders, thus compromising the participatory design process. A balance must be made regarding how ergonomics tools and user knowledge are managed and applied in projects, and by what participating stakeholder groups.

- GA drawings are a common platform which seafarers, ergonomists and designers can communicate through. Visual representations aid storytelling and contextualize onboard crew work and demands for designers. GA drawings facilitate dialogue between crew and naval architects where tangible design solutions can be discussed, described visually and optimized by improved, user-centred design solutions.

- As an ergonomics analysis tool, GA drawings are not a completely accurate representation of the finalized work environment, nor provide the possibility for comprehensive work environment analyses. However, valuable information can be extracted from basic 2D GA drawings and initial design sketching that can be used to provide input throughout ship development. Primarily, this includes the evaluation of the physical characteristics of work areas (e.g. layout, dimensions, access points and logistics) in relation to crew work demands throughout a ship structure. Crew work tasks and movement patterns (whether normal operation or emergency situations) can be mapped in GA drawings revealing high traffic areas, distances and layout between specific work sites/equipment, thus creating an evaluation and optimization process.

The long-term success of ergonomics in shipping demands the demonstration of measurable, cost-efficient results which lead to tangible design improvements and return on investment. The data collections and developed solutions attempted to adapt to naval architecture design methodologies in order to facilitate integration and utilization by designers. Although the scope of this thesis focused on developing methodologies and technical solutions directly related to ship design and naval architecture work processes, naval architects and shipping industry stakeholders require increased training and education to better understand the added value of ergonomics applications for the industry. Utilizing distributed participatory design practices throughout new ship development can contribute optimized user-centred ship design and layout solutions, and ultimately improve onboard work environments for its crew and operations.

Chapter 8

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