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Towards a Pluralistic Epistemology: Understanding the Future of Human-Technology Interactions in Shipping

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Cover image illustration: The author of cover image is a well-known Chinese artist, Xutong Tian, who is a professor in Academy of Arts & Design in Tsinghua University. He mostly works with contemporary ink art in a cultural-historical language to reflect old laws in oriental philosophy. His breathtaking Zen paintings reflect a mindfulness status that I have been experienced in exploring the relationship between humans and technology. I believe art is a thought-provoking language that is philosophically edifying for researchers. I deeply appreciate him for allowing me to use his work as the cover image, as a motivator for all the readers to contemplate the world we live in.

To my families,

who make me live, laugh and love.

"The effects of the design extend beyond the software itself to include the experiences that people will have in encountering and using that software. Designing for the full range of human experience may well be the theme for the next generation of discourse about software design."

- Terry Winograd

Abstract

The rapid advance of technologies is revolutionizing the way people work and transforming society into a digital world. In the shipping domain, many innovative technical systems have been designed and developed in the past decades, aiming to enable the maritime users to achieve the goal of safety, efficiency and effectiveness. The introduction of advanced technologies into workplaces that are intended to aid humans have also created unprecedented challenges. As their workplaces are inundated with new artefacts that cause confusion and information overloading, human users frequently find themselves in a supporting role to serve technology, being responsible for automation issues and blamed for "human errors" that sometimes result in tragic results. Today's work in shipping is generally getting more distributed, complex and demanding.

These challenges are closely associated with the design and use of technologies. Human-technology interactions in the context of sociotechnical systems has become an important research topic. It explores the relation between humans and machines to illustrate how interface design could address the human limitations, shape social interactions and provide ecological implications. This thesis considers the context of the shipping domain to investigate the impact of innovative technology, design issues and opportunities in various projects that attempt to increase safety or/and efficiency. The exploration and discourse in these applied projects are positioned in sociotechnical systems which include human, technology and organisational constituents. The thesis aims to achieve a deeper understanding of human-technology interactions from psychological, sociological and ecological perspectives, reflecting the ways in which technology interacts with humans. It aims to form a pluralistic epistemology to provide design implications and enlighten knowledge and organisational management within sociotechnical systems.

The results have identified many issues related to situation awareness, attention and automation bias. It suggests the importance of adapting interfaces to the human limitations and accommodating the context change to support decision making. Perspectives of Activity Theory, distributed cognition and situated learning have high reference value in human-computer interaction research, providing insightful understanding about the nature of knowledge and interaction design, particularly how tool mediation could facilitate social interaction. In addition, technology-centric design that only concerns "user-interface" interaction is identified having significant limitations in complex systems. "Human errors" and organisational failures should be perceived via a holistic thinking. The results have presented the importance of adopting pluralistic approaches to understand the sociological factors and the nature of the work that is undergoing transitions along the shipping industry's ecology.

Overall, the thesis has identified the need to go beyond the pure cognitivist approach to better understand the complexity of human-computer interaction and human factors research, forming a deepened understanding towards an emerging interdisciplinary language of sociotechnical systems. To truly contribute to safety, efficiency, effectiveness and sustainability, it is critical to develop a pluralistic epistemology and a comprehensive human-centric vision regarding design and technological innovation in the digital revolution.

Keywords: Human-Technology Interaction, Human Factors, Human Errors, Situation Awareness, Automation, Decision Making, Activity Theory, Situated Learning, Distributed Cognition, Human-Computer Interaction, Psychology, Sociology, Ecology, Complexity, Knowledge Management, Sociotechnical System, Maritime, Multidisciplinary, Epistemological Pluralism

List of Publications

Appended Articles

ARTICLE I

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ARTICLE II

Man Y., Lützhöft M., Costa N.A., Lundh M., MacKinnon S.N. (2018). *Gaps between Users and Designers: A Usability Study about a Tablet-Based Application Used on Ship Bridges*. In: Stanton N. (eds) Advances in Human Aspects of Transportation. AHFE 2017. Advances in Intelligent Systems and Computing, vol 597. Springer, Cham. doi: 10.1007/978-3-319-60441-1_21

ARTICLE III

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ARTICLE V

Man, Y., Lundh, M., & MacKinnon, S. N. (2018). *Managing Unruly Technologies in the Engine Control Room: from Problem Patching to an Architectural Thinking and Standardisation*. WMU journal of Maritime Affairs, 1-23. doi: 10.1007/s13437-018-0159-y

ARTICLE VI

Man, Y., Weber, R., Cimbritz, J., Lundh, M., & MacKinnon, S.N. (2018). *Human Factors Issues During Remote Ship Monitoring Tasks: An Ecological Lesson for System Design in a Distributed Context*. International Journal of Industrial Ergonomics, 68, 231-244. doi: 10.1016/j.ergon.2018.08.005

Additional Relevant Publications

Porathe, T., Prison, J., & Man, Y. (2014). *Situation awareness in remote control centres for unmanned ships*. Paper presented at the RINA Human Factors in Ship Design and Operation Conference, London, UK.

Man, Y., Lundh, M., & Porathe, T. (2014). *Seeking harmony in shore-based unmanned ship handling – From the perspective of human factors, what is the difference we need to focus on from being onboard to onshore*. Paper presented at the 5th International Conference on Applied Human Factors and Ergonomics and the Affiliated Conferences, Krakow, Poland.

MacKinnon, S., Man, Y., Lundh, M., & Porathe, T. (2015). *Command and Control of Unmanned Vessels: Keep Shore Based Operators In-The-Loop*. Paper presented at the NAV 2015 18th International Conference on Ships and Shipping Research, Milan, Italy.

Lundh, M., MacKinnon, S., & Man, Y. (2015). *Transparency within automated engine control systems: The case of the Savannah Express*. Paper presented at the NAV 2015 18th International Conference on Ships and Shipping Research, Milan, Italy.

Rylander, R., & Man, Y. (2016). *Autonomous safety on vessels - an international overview and trends within the transport sector*. Lighthouse Report. Gothenburg, Sweden: Lighthouse.

Lundh, M., Aylward, K., MacKinnon, S., & Man, Y. (2017). *On the adaption of the Guidelines for engine-room layout, design and arrangement MSC/Circ.834*. Report for Intertanko. Gothenburg, Sweden: Chalmers University of Technology.

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List of Abbreviations

ACD	Activity Centred Design (ACD)
AH	Abstraction Hierarchy
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
CA	Collision Avoidance
COLREG	International Regulations for Preventing Collisions at Sea
CSCL	Computer Supported Collaborative Learning
CSCW	Computer Supported Cooperative Work
CWA	Cognitive Work Analysis
DOA	Degree of Automation
ECDIS	Electronic Chart Display and Information System
ECR	Engine Control Room
EE	Energy Efficiency
EID	Ecological Interface Design
ETA	Estimated Time of Arrival
GOTRIS	Göta älv River Information Services
HCI	Human Computer Interaction
HMI	Human Machine Interaction
ICT	Information and Communication Technology
ID	Interface Design
IEC	International Electrotechnical Commission

IT	Information Technology
IMO	International Maritime Organization
ISO	International Organization for Standardisation
LOA	Level of Automation
MUNIN	Maritime Unmanned Navigation through Intelligence in Networks
NASA	National Aeronautics and Space Administration
QIUSS	Quality In Use Scoring Scale
RQ	Research Question
SA	Situation Awareness
SART	Situation Awareness Rating Technique
SCC	Shore-based Control Centre
SEEMP	Ship Energy Efficiency Management Plan
SME	Subject Matter Expert
SRK	Skill, Rule and Knowledge
STM	Sea Traffic Management

Chapter 1: Introduction

Merchant shipping has been historically an important aspect of the world economy and it has a profound impact on human civilisation. Approximately ninety percent of the world trade is carried on the sea with over seventy percent as containerized cargo (Castonguay, 2009) and is largely due to the fact that shipping remains to be the most economical form of transportation when moving goods over long distances (Ashmawy, 2012).

However, work at sea or near water has always been characterised as high risk occupations based on its history and culture (Håvold, 2015; Hetherington, Flin, & Mearns, 2006). Seafaring, once was described as the original 24 hour society (Filor, 1996). In an enclosed space, the ship's crew have to undertake demanding physical and cognitive activities (Mallam, 2014) and deal with problems in difficult situations when a ship is in distress and life of those onboard are threatened (Lundh, 2010). Work pressure, fatigue, environmental factors and long periods of time away from home contribute to these high work stresses (Hetherington et al., 2006). In a way, the work demands within the shipping industry contrast other industries as much more stress and pressure from seafarers have been reported than other vocations (Parker, Hubinger, Green, Sargent, & Boyd, 2002). Thirty nine percent of incidents at sea describe fatigue as a contributory factor of accidents (Phillips, 2000). High degrees of fatigue and stress reduce awareness, productivity and lead to higher risk of making mistakes (Håvold, 2015; Trakada, Chrousos, Pejovic, & Vgontzas, 2007).

In addition to safety issues, economic and environmental concerns have also increased considerably in the shipping industry to deal with the challenges in growth and transport sustainability demands (Bhattacharya, 2015). Improving energy efficiency has been recognised as the key factor to reduce the maritime footprint upon greenhouse gas emission in recognition of climate change challenges (Buhaug et al., 2009; IMO, 2014b). Similarly, reducing fuel consumption while maintaining the same level of transportation service should lead to increased profitability (Bännstrand, Jönsson, Johnson, & Karlsson, 2016).

Rapid advances in technologies appear to provide solutions to improve productivity and safety. As a competitive industry (Stopford, 2009), shipping has been involved in the global wave of computerisation in an attempt to enhance safety, effectiveness and efficiency of sea transportation operations, to save energy and increase profitability and competitiveness (Allen, 2009; Grech, 2008; Ljung & Lützhöft, 2014). From paper chart and compass in the analog world to all kinds of computerised navigational or monitoring systems in a digital world, shipping has always been undergoing a transition. Today, there are many automated systems and Information Technology (IT) applications that have been designed, developed and deployed in the maritime domain. These tools provide both shipboard and shore-based users unprecedented opportunities to enhance operational practices and access information in pursuit of higher efficiency, effectiveness and safety. If we take a modern ship bridge as an example, it has assimilated many technologies at a very fast pace, with such examples as the autopilot or ARPA (Automatic Radar Plotting Aid), which has gradually changed the navigators' roles to more planning and monitoring related tasks in the current phase of human-technology interaction, where the next stage could be conducting unmanned ships related operations (Conceição, Carmo, Dahlman, & Ferreira, 2018).

The two key words that may best characterise the ongoing transition in the shipping domain are digitalisation and automation. According to the Gartner IT glossary, digitalisation is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities (Gartner, 2018). For example the introduction of virtual and augmented reality provides new platforms to support training, retrofitting and design solutions (Lukas, 2010); the adoption of cloud computing reveals great opportunities from scalable computation, security improvement and resource management (Gentzsch, Purwanto, & Reyer, 2016; Heilig & Voß, 2016). Increasing interest or utilization of the big data concept (Koga, 2015; Rødseth, Perera, & Mo, 2016) and blockchain (Park, 2018) creates huge potentials to be more effective and safer. One of the major ongoing international developments is e-Navigation, which proposes to use electronic means to harmonize "collection, integration, exchange, presentation and analysis of marine information on board and ashore, enhance navigation and related services for safety and security at sea" (IMO, 2014a). Many innovation projects regarding information and communication technology (ICT) have been carried out in the European Union under the umbrella of e-Navigation. As examples of European Union funded programmes, Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) studied the feasibility of autonomous unmanned ships, Sea Traffic Management (STM) focused on efficient data exchange between ships and ports and EfficienSea2 aimed to create and implement solutions for efficient, safe and sustainable traffic at sea through improved connectivity for ships. It is noteworthy that, although digitalisation appears to have a profound impact on navigational safety, cargo management, ship/terminal integration, and customer service, only 30.4% shipping companies have implemented or are currently implementing a digitalisation strategy based on the Shipping Industry Survey (RINA, 2018). At the same time, autonomy points to what the shipping industry wants to achieve in the future (Rylander & Man, 2016), by developing technologies to enable some form of self-governance (Rødseth & Nordahl, 2017). The prevalence of automation onboard has been increasingly desired by ship-owners to reduce manning levels in order to cut costs (Hummels, 2007). Beside MUNIN, many other projects regarding autonomous ships have been launched in the past several years (Aplin, 2015; MarEx, 2018). All these depict a picture of development transition of shipping, a slowly evolving but highly tech-driven industry (see Figure 1).

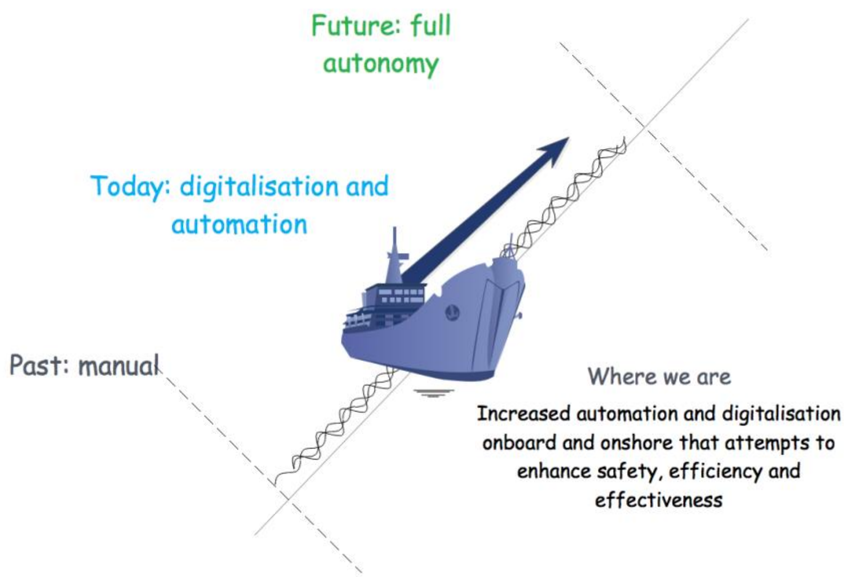

Figure 1. With increased digitalisation and automation, the shipping industry is at a full speed towards autonomy in this transition period.

However, the way to incorporate digitalisation and autonomy into the maritime domain is questionable. Paradoxically adding technologies does not necessarily improve safety and productivity. The rapid introduction of IT solutions without full recognition to the human element and adaptation (Grech, 2008; Hetherington et al., 2006; Landauer, 1995) has been dominantly technology-centric. Shipping industry is a slow-moving industry in policies and regulations, governed by both international legislation and regional / national laws (Paixao & Marlow, 2001). Technology introduction on board moves much faster than regulatory development. Given this reality the shipping industry lags behind other safety critical industries. Thus, rapid technological advancements create unprecedented challenges and gaps: often these systems usually have little considerations for integration with or cognitive capabilities of the users (Lundh & Rydstedt, 2016; Lützhöft & Dekker, 2002; Lützhöft, Lundh, & Porathe, 2013). The work demands have been altered including increased administrative tasks, inadequate skill development and steep learning curves due to reduced crews and rapid change in automation technology (Ljung & Lützhöft, 2014; Lundh, Lützhöft, Rydstedt, & Dahlman, 2011). In addition, a lack of equipment standardisation and poor usability have brought about information overload issues (Grech, 2008). Fast introduction of technology is also influencing the crew's traditional learning experience (Oliveira, Costa, & Torvatn, 2016), affecting how workers communicate and coordinate with each other (Lützhöft, 2004; Lützhöft & Nyce, 2008). From a more macroscopic perspective to look at the digitalisation development strategy, the slow regulatory progression from the International Maritime Organisation (IMO), shipping's highest regulatory body, has also compounded the complexity (Mallam & Lundh, 2013; Wagner, Lundh, & Grundevik, 2008). The typical reaction to an accident has been training and changing of procedures where systemic evaluations or proactive policies have rarely been developed (Schröder-Hinrichs, Hollnagel, Baldauf, Hofmann, & Kataria, 2013). Therefore, what we see today are "human errors" (regarding humans) and automation issues (regarding machines) in many maritime accident reports and studies (House & Place, 2006; Rothblum, 2000; Sandhåland, Oltedal, & Eid, 2015). What we see is "clumsy automation", a form of poor coordination between humans and machines, which is believed to account for incidents (Grech, Horberry, & Smith, 2002). What we see is the ill-design of technology which makes users deploy and use the systems in ways that are not expected by regulators and manufacturers (Grech & Lemon, 2015; MAIB, 2016). The systems may also behave in a way not expected by users, e.g., in the form of "automation surprise" (Ahvenjärvi, 2011; Lützhöft & Dekker, 2002) such as the automated systems act autonomously and the users may find it hard to understand the machine's true state based on limited feedback (lack of transparency). In short, what we see in the shipping industry today is the intricate interactions among multiple stakeholders (e.g., port authorities, ship owners, service providers, equipment manufacturers, and domestic and international regulators) (Caschili & Medda, 2012; Kaluza, Kölzsch, Gastner, & Blasius, 2010) and a lagging behind regulatory development (Han & Ding, 2013; Mallam & Lundh, 2013) that is heavily propelled by fast-emerging technologies.

Industrial systems are extremely large and complex with tighter coupling, more interconnections and interactions, when they were described by Perrow (1984). Today they are increasingly distributed in terms of space, time and function. In the maritime domain, shipping, logistics and management are going to be performed in a completely different way in the future as advanced and yet to be described technologies are introduced. These problems and gaps in shipping are largely concerned with human capabilities, fallibility and characteristics, which are essentially about local human-technology interactions which today are the main focus of classic human factors research (Karwowski, 2005). It is understandable to emphasise the human limitations when we come to issues pertinent to the interaction process, e.g., researchers have been advocating "systematic use of knowledge concerning relevant human characteristics in order to achieve compatibility in the design of interactive systems…" (HFES, 2004). In fact, Human Machine Interaction (HMI) research traditionally focused on the human behaviours in interacting with computing technology of some sort (Card, Newell, & Moran, 1983; MacKenzie, 2012) or usability engineering in a dyadic closed-loop human-machine system (Lim & Long, 1994). Spawned from the human factors community (which derives from the problems of designing controls for humans during World War II) and many other older disciplines, Human Computer Interaction (HCI), as a field of study, emerged in the 80's (e.g., the first conference on Human Factors in Computing Systems was held in 1982 which later turned to the annual ACM SIGCHI conference) (Lazar, Feng, & Hochheiser, 2017). Over the years, HMI/HCI has also been growing in scope and range to address the challenges in complex systems and looks beyond local systems (Behymer & Flach, 2016; Hollnagel, 2011) to a more "broadly defined human-technology interactions" (Karwowski, 2005).

In the whitepaper of an international project about autonomous shipping funded by Finnish Funding Agency for Technology and Innovation, it is mentioned that "in addition to the interactions of the various components and sub-systems in the technology, human operators and human-technology interaction remain even more important elements in this implementation" (AAWA, 2016, p. 62). In a textbook of human factors in the maritime domain, a few "examples of HMI problems" on ships are listed, e.g., lack of equipment usability and standardisation, over-reliance on technology, rapid changes in technology, ignoring human factors in the design and development (Grech, 2008). How HMI/HCI (or human-technology interaction as a more general term) is perceived and understood in the shipping domain remains to be explored. The shipping industry, which is increasingly inundated with new technological artefacts and innovations, is at a critical crossroads towards improvements in safety and effectiveness. Thus, it becomes an ideal targeting context to understand the complexity of human-technology interaction from different research directions, which is ultimately directed towards improved safety, efficiency and effectiveness for the shipping business. This perspective directs the applied context for this thesis. The wide-scope issues in the transition phase of shipping established a niche for HCI research to employ a multidisciplinary approach to gain deeper understandings about 1) the way in which technology interacts with us humans and our cognition; 2) their roles in our human social activities; and 3) how the shipping industry is about to proceed by extending our control and shaping the eco-system. In the context of this thesis, human-technology interaction looks at the design and use of technology from the psychological, sociological and ecological perspectives. This is to explore the impacts of advanced technologies and probe how digitalisation and automation should be designed to not only facilitate information processing, but also learning and collaboration in their work as well as the user-work coupling and development of the global eco-system. Considering the complexity of the issues and the world realities, the underlying philosophical *worldview* (i.e., a basic set of beliefs that guide action) (Creswell, 2014; Guba, 1990) or *epistemology* (Crotty, 1998) is considered to be pluralism that is associated with recognition and acceptance of multiplicity and diversity (O'Leary, 2007).

1.1 Research Background, Scope and Aim

Background:

The rapid advance of technologies is revolutionizing today's shipping industry towards a digital world, where human operators need to work with computerised systems in more demanding and complex tasks while designers need to create diverse innovative IT solutions to meet various needs. A deeper understanding of the issues with respect to design and use of technologies as well as management practices first requires a *comprehensive* multidisciplinary view to understand human-technology interaction. Though HCI itself broadly draw upon interests and expertise from various disciplines like cognitive science, engineering, sociology, etc., its research and utilisation in the maritime world are perhaps still far from multidisciplinary or interdisciplinary. The thesis has considered several maritime projects which are all characterised by advanced digitalisation and/or autonomation solutions, in order to provide a multi-epistemological understanding of human-technology interaction as well as contribute to better future design of technologies in shipping. The exploration and discourse are positioned to explore the interactions of human, technology and organisational constituents. The projects include shore-based control centre development in the autonomous unmanned ship project (MUNIN), tablet-based service for bridge opening information coordination project (GOTRIS, Göta älv River Information Services), Energy Efficiency (EE) optimisation project, maritime connectivity platform (EfficienSea 2 project). The projects had their own specific context but they all involved advanced digitalisation or/and automation development and the human element in complex maritime sociotechnical systems. They are development examples of a few very representative sectors in shipping, such as energy efficiency, autonomous shipping, and digitalisation of tools and equipment used onboard. The projects were highly technology-driven and developed mainly by people with technical backgrounds who usually are more tech-savvy and less concerned with human-machine interaction. These realities considered in this thesis reveal the complex nature of the shipping domain, suggesting the need to incorporate a multidisciplinary view of human-technology interaction for research, design and engineering. To see human-technology interaction through different lenses may set up an important foundation to allow reflecting and synthesising links between required disciplines in pursuit of a coherent whole (i.e., arriving at an interdisciplinary perspective ultimately). Such an approach is viable because of the general context of all these technology-driven projects share. Although these research projects are conducted in their own shipping domain context and may appear to be independent from each other, they all not isolated per se:

1) All of these projects encompass state-of-the-art technologies in the shipping domain and contribute to considerations of design and use of technology as well as the overarching theme of human-technology interaction. The collection of maritime studies has been conducted to explore the opportunities and challenges of both digitalisation (e.g., IT applications or digital services that aim to improve safety/efficiency) and/or automations (e.g., autonomous ships) in multiple dimensions. The focus is on the reciprocal relationship between technologies and human activities, i.e., how these technologies influence human performance, how the users' needs and work demands could shape the artefacts.
2) By multiple dimensions, it means the collection of maritime studies aim to present a multidisciplinary research practice to cover a relatively broader range of HCI to think both "small" and "big" (Schröder-Hinrichs et al., 2013). These projects are so connected under the theme of human-technology interaction that they give us new angles to understand HCI. It is not just important to explore how to tailor technologies to match the human operator's capabilities and limitations but shall discuss how to employ "languages" other than traditional psychological approaches to explore social interactions and ecological implications. The acceptance of need for multiplicity in human factors theory and knowledge is increasing and the analysis and evaluations should really allow for the possibility of emergence from the potentially inter-connected aspects (Wilson, 2014). Taking multiple dimensions may help researchers to find connections and integrate disciplinary knowledge in a way to form a real synthesis to better understand human-

technology interaction. My comprehension of HCI evolved from cognitive psychology towards a multidisciplinary understanding, preparing HCI researchers to find means to develop an interdisciplinary framework in future research. This could be the theoretical contributions to integrating the current research silos (e.g., only concerning about information processing, social interactions or design solutions). However, this should be not seen as a simple advocation of paradigm shift from one dimension (e.g., looking at local problems: human-computer interaction as such, interface design and usability) to another (e.g., looking at global problems: social interaction and ecological implications) but this should be taking a more inclusive framework to understand the human factors related issues in the shipping environment. It is rather a process of forming a pluralistic epistemology that has the potentials to harmonise the transition period.

Scope:

The scope of this thesis is to use the applied research projects and practices that attempt to increase safety or/and efficiency in the maritime domain to:

1) Explore the impacts of new IT applications in the maritime domain on human performance from the psychological, sociological and ecological perspectives and identify gaps that in the design and use of the technology;
2) Understand the role of human users and technological artefacts and how/why context matters in human-technology interaction;
3) Synthesise models, theories and knowledge pertinent to HCI to form a pluralistic epistemology for future maritime development and HCI research.

Aim:

The aim of the thesis is to achieve a deeper understanding of human-technology interaction and reflect upon the ways in which digitalisation and automation technology interacts with humans in the maritime context. It is expected to generate theoretically insightful and usable knowledge to comprehend the challenges with the advent of fast introducing technologies. It aims to contribute to future maritime development and HCI research, and dissolve (rather than solve) the issues in human-technology systems such as "human errors" and "automation issues" in a way to hopefully edify future design. It also aims to form a pluralistic epistemology that can not only provide design implications as applied solutions but also enlighten knowledge and organisational management in the theoretical sense.

1.2 Research Questions

The discourse of the project experience will mainly discuss how humans engage with digitalisation and/or automation in the specific context and its psychological, sociological and ecological implications. The research questions (RQs) are thus formulated in the following:

1) RQ1:
   How do the advanced technologies in the shipping domain impact human performance and work, and what are the prominent human factors related challenges and gaps in the design and use of digitalisation or/and automation technologies?
2) RQ2:

How can human-technology interactions be explained through the psychological (e.g., information processing-based approaches), sociological (e.g., social-cultural aspects of work, technologies' potentials in affecting collaborative learning practice, knowledge mobilisation, communication) and ecological lenses (e.g., user-work coupling, systems thinking, eco-system development) in the shipping domain?

3) RQ3:
What are potential values for a multidisciplinary approach to understand the human factors related challenges in the shipping context?

1.3 Delimitations and Limitations

Shipping in this thesis only addresses maritime shipping. This thesis is mainly a discourse of exploratory research in digitalisation and automation sectors of the shipping domain rather than a traditional HCI laboratory-based study on a fixed topic where different designs are compared through controlled experiments. The included maritime projects aim to provide the detailed research context for the discussion of design and use of technology. Finding the synergies through participating, as a researcher, in various projects whose goals and applied context are distinct could be considered as a philosophical endeavour to seek interdisciplinary implications. The psychological, sociological and ecological perspectives to understand human-technology interaction should not be seen as the only legitimate dimensions to synthesise the disciplinary knowledge in HCI research, but they do glue the collection of seemingly independent studies together to present the dilemma in the shipping industry. These perspectives also suggest the values of a multidisciplinary lens and moving towards an interdisciplinary approach in order to understand the complex issues residing in human-technology interaction.

A limitation is that some studies in the thesis are conceptual papers with literature reviews so it might be the case that some arguments for proposing the way ahead are hypothetical, which may still enlighten the future maritime human factors research directions. The knowledge development in the doctoral programme was accumulated with experiences in different studies, related to those aspects to be introduced in the following chapter of theoretical framework. Exploratory research usually takes place when problems are in a preliminary stage to help determine an appropriate research design approach or direction (e.g., in article VI it was discussed why cognitive work analysis would likely be promising for future research to be applied in the technology-centric maritime context). However, it should be noted that the goal is neither to solve the discovered issues by presenting perfect engineering solutions that pass certain hypothesis validation nor to present a comprehensive work analysis in the first place. Although all studies have discussed the impact of representative maritime digitalisation and automation applications, it does not aim to generalise the findings for every piece of innovative IT services or applications in the industry. Instead, the discourse attempts to raise the awareness of issues in the maritime domain with fast introducing technologies and develop more in-depth understandings of human-technology interaction through a multidisciplinary lens. The collection of different articles together tries to advocate an attitude of having a pluralistic epistemology in future maritime research. Despite the limitations brought by different contextual scenarios and applications, it is still promising to gain the insights about human errors, interaction design and complexity of sociotechnical systems for other safety-critical work domains.

1.4 Appended Articles

In the laboratory studies (e.g., MUNIN and GOTRIS Projects) or field studies (e.g., Enery Efficiency Project) used in this thesis, Yemao Man's contributions include, but are not limited to, research design, literature studies, data collection and analysis. He is the first author and main contributor of all appended articles, while the co-authors assisted or supervised the development.

Article I

Citation:	Man, Y., Lundh, M., Porathe, T., & MacKinnon, S. (2015). *From Desk To Field - Human Factors Issues In Remote Monitoring and Controlling of Autonomous Unmanned Vessels*. Procedia Manufacturing, Volume 3, Pages 2674-2681. Paper presented at the 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, Las Vegas, USA. doi: 10.1016/j.promfg.2015.07.635
Summary:	The purpose of this study was to explore the human factors related issues in remote monitoring and controlling of autonomous unmanned vessels through scenario-based trials. The literature review and fieldwork data identified several gaps in the current autonomous ship's supervisory control concept, suggesting aspects on which the design could be improved to enhance operator's situation awareness.
Contribution to the research question:	This article contributes to answer RQ1 and RQ2. The study examined the human performance and identified gaps mainly from the psychological perspective, revealing what issues the operators have been confronting with increasing automation in shipping. It also discussed the underlying organisational issues and importance of the context.

Article II

Citation:	Man Y., Lützhöft M., Costa N.A., Lundh M., MacKinnon S.N. (2018). *Gaps Between Users and Designers: A Usability Study About a Tablet-Based Application Used on Ship Bridges*. In: Stanton N. (eds) Advances in Human Aspects of Transportation. AHFE 2017. Advances in Intelligent Systems and Computing, vol 597. Springer, Cham. doi: 10.1007/978-3-319-60441-1_21
Summary:	Although there is substantial research on usability, the values and usability of the tablet-based applications used on ship bridges have rarely been investigated. In this paper, a tablet-based computer application was developed to provide decision support to river pilots for passing under bridges in the Gothenburg area. Experienced pilots were invited to participate in a simulated navigational environment. By exploring the problems in using such novel digitalisation application on a bridge, this study aims to address the gaps in the maritime IT design and shed light on the future developments.
Contribution to the research questions:	This article contributes to answer RQ1 and RQ2. This study examined the user experience and usability issues of the introduced technology mainly from a psychological perspective. It uncovered some significant problems in design

and use of IT services as digitalisation means and suggested the value of considering work ecology in design.

Article III

Citation:	Man, Y., Lundh, M., & MacKinnon, S. N. (2018). *Maritime energy efficiency in a sociotechnical system: A collaborative learning synergy via mediating technologies*. The International Journal on Marine Navigation and Safety of Sea Transportation, 2018. 12(2). doi:10.12716/1001.12.02.03
Summary:	This paper described the essence of practitioners' activities and explored the nature of interaction design and proposed improved design for energy efficiency (EE) monitoring systems. Findings suggested that knowledge sharing for a mutual understanding onboard ships is critical to energy efficiency. Learning can go beyond the embodiment of individual cognitive change but becomes a collective and collaborative achievement mediated by technology, which informs opportunities for future interaction design.
Contribution to the research questions:	This article contributes to answer RQ1 and RQ2. This study not only reviewed the human performance issues with increasing demand on EE but also used a socio-cultural perspective to understand if and how the identified gaps could be mitigated. It went beyond the pure cognitive approach to understand the concept of learning. The study also discussed the reciprocal relationship of human activities and technology design (concerning the roles for human and technology), suggesting interaction design in a broader context.

Article IV

Citation:	Man, Y., Lundh, M., & MacKinnon, S. N. (2018). *Facing the New Technology Landscape in the Maritime Domain: Knowledge Mobilisation, Networks and Management in Human-Machine Collaboration*. Paper presented at the 9th International Conference on Applied Human Factors and Ergonomics and the Affiliated Conferences, AHFE 2018, Orlando, Florida, USA. doi: 10.1007/978-3-319-93885-1_21
Summary:	This paper used the practice of EE onboard ships as an example to discuss how knowledge mobilisation should address this context change and uncovers how existing knowledge networks in the shipping industry would evolve in this emerging data-driven ecology. From the systems perspective, it suggested hallmarks associated with the knowledge mobilisation processes in the new technology landscape.
Contribution to the research questions:	This article contributes to answer RQ1 and RQ2. This study used social-ecological perspectives to describe the potential impact on knowledge mobilisation and management practices in the ship domain with intelligent digitalisation or/and automation solutions. It also discussed the roles of human and technology as well as values in systems thinking in a human-machine collaboration context.

Article V

Citation**:**	Man, Y., Lundh, M., & MacKinnon, S. N. (2018). *Managing Unruly Technologies in the Engine Control Room: from Problem Patching to an Architectural Thinking and Standardisation*. Submitted to WMU journal of Maritime Affairs on April 17th 2018. Manuscript accepted on October 19th 2018. doi: 10.1007/s13437-018-0159-y
Summary:	This article contributes to answer RQ1 and RQ2. This conceptual paper re-examined a design case in an ECR on a merchant ship and discussed the potentials of a service-oriented architectural approach to manage emerging unruly technologies and integrate distributed resources in the maritime human-technology system. It suggested a shift of focus from patching individual problems locally to holistic systems views on the maritime eco-system development globally.
Contributions to the research questions:	This study employed a holistic perspective to identify the issues and gaps in the design and deployment of technologies in the shipping's eco-systems and proposed a possible solution to deal with complexity in the shipping business.

Article VI

Citation:	Man, Y., Weber, R., Cimbritz, J., Lundh, M., & MacKinnon, S.N. (2018). *Human Factors Issues During Remote Ship Monitoring Tasks: An Ecological Lesson for System Design in a Distributed Context*. International Journal of Industrial Ergonomics, 68, 231-244. doi: 10.1016/j.ergon.2018.08.005
Summary:	In this paper, a remote supervisory control prototype was developed on top of a fully-fledged ship bridge system to support monitoring and controlling of remote simulated unmanned cargo vessels. Six participants were invited to conduct scenario-based simulation trials and their objective performance and subjective SA assessment was collected and analyzed. The results suggested human factors related issues could remain in systems assembled by assumed reliable technological components. This paper has important relevance to sociotechnical system and interface design that the design also needs to take the context and environmental constraints into account through an ecological approach.
Contributions to the research questions:	This study took a psychological perspective to investigate how advanced technology could impact human performance (similar to Article I) and explained the current gaps by reflecting the ecological implications. It suggested that the ecological considerations should be further appreciated in the design of the maritime technology-centric projects that aim to have a profound impact on the future shipping work domains.

Through taking multiple perspectives to understand human-technology interaction in the shipping context, these six articles directly contribute to answer RQ1 and RQ2 and all together contribute to answer RQ3. This thesis aims to summarise and synthesise findings across studies, a multidisciplinary lens serve as a starting point to describe 1) how the author explored the human factors related challenges with increased digitalisation and automation in the shipping domain; 2) how the author improved his understanding towards the design and use of technology from psychological, sociological and ecological perspectives (Figure 2); 3) how the author gradually learned the value of a pluralistic epistemology and the need to move towards interdisciplinary approaches in future research.

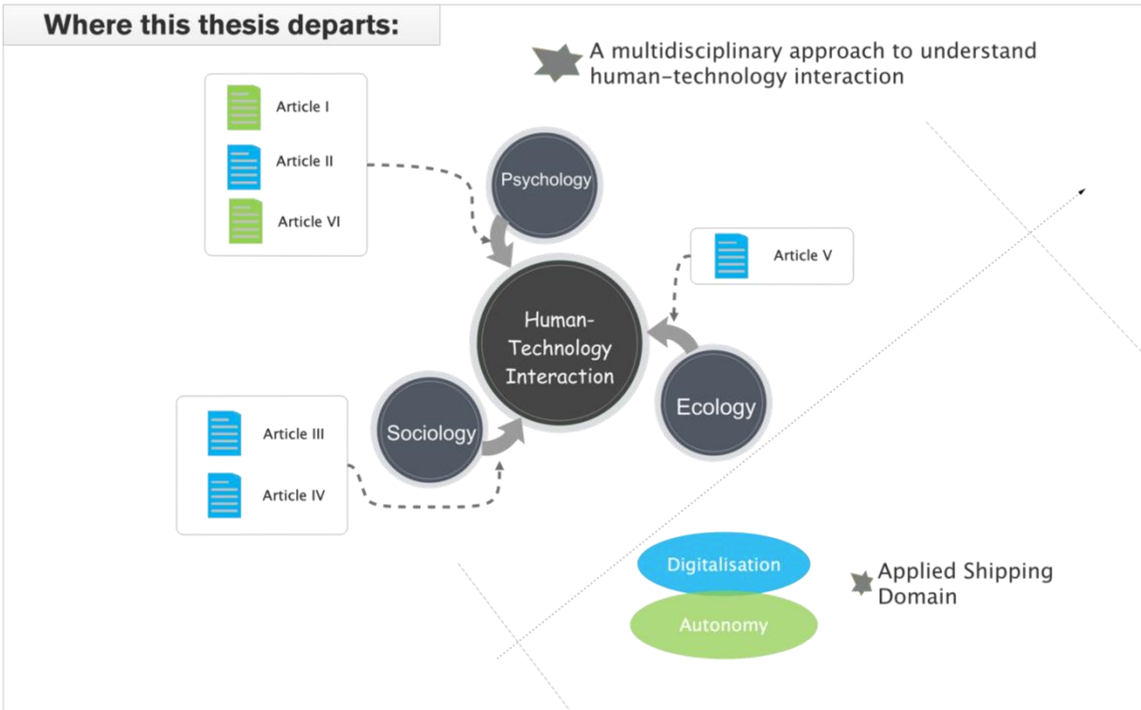

Figure 2. A dipiction of where this thesis departs.

1.5 Thesis Structure

This thesis consists of seven chapters and an appendix containing the six peer-review articles. Chapter 1 presents a general introduction to the maritime context and issues in human-technology interaction. The RQs and scope are also listed. Chapter 2 presents the theoretical framework of the thesis by reviewing the research literature with respect to psychological, sociological and ecological perspectives. Chapter 3 presents an overview of the research approach, methods and procedures. Chapter 4 reports selected main findings from the appended articles. Chapter 5 provides a broader discussion on design and system approaches based on the findings. Chapter 6 summarises the main conclusions from the perspective of psychology, sociology and ecology as well as highlights the research contribution of the thesis. Chapter 7 provides all references used within the thesis.

Chapter 2: Theoretical Framework

Although parts of the RQs are related to design about how to make the IT systems more usable, efficient and effective for human being thus making the research papers appended to this thesis seem to be engineering-oriented, the topic of human-technology interaction is fundamentally interdisciplinary, situated largely in the intersection between multiple disciplines (Carroll, 1997). Psychology, a study of the human mind and its functions (Wolff, 2010), can provide guidelines for developers and verify the usability of systems (Carroll, 1997) based on basic cognitive constraints and essential decision making processes (Wickens, 1992). Sociology, a study of human society including social relationship and social interaction (ASANET, 2008), is going to help us to expand the lens to the social-cultural aspects of work in the context of technology use (Hutchins, 1995; Kaptelinin & Nardi, 2006; Lave, 1988; Suchman, 2007). In the recent decades, the ecological aspect has also obtained more attention in this intersection (Flach, 1995b). Ecology, originating from biological studies that deals with the relations of organisms to one another and to their surroundings (Gibson, 1979), is going to help us to scrutinize fundamental phenomenon of human-technology interaction with concerns on human experience and interface design (Bennett & Flach, 2011; Rasmussen, Pejtersen, & Goodstein, 1994). In order to explore how technologies affect human performance, issues in the design and use of these artefacts and ways to improve the design, it is necessary for us to first understand some of the important constructs pertinent to the interconnected themes of psychology, sociology and ecology.

Cognitive psychology has traditionally been understood as the main body of HCI research, e.g., how people perceive information, how their memory works to remember the information and how they come up rational decisions. The relevant cognitive concerns that need to be incorporated into the design in the field will be introduced in section 2.1. The limitations of this approach and values of considering sociological and ecological lenses will be introduced in section 2.2 and 2.3 to enrich the theoretical framework. The goal of this academic endeavour is to form an inclusive framework in which interconnected theoretical dimensions are systematically organised, thus different "languages" could be spoken in different contexts depending on the project goals and settings and may be harmonised into a coordinated whole in future research. The concentration of the doctoral education is not about taking a stance to limit oneself in a certain academic tradition or factions but gaining knowledge about establishing a position to embrace the opportunities to look at problems dialectically. The critical review of the psychological, sociological and ecological realms would not only aim to elucidate the theoretical context in which different studies were implemented, but also provide a basis to discuss the values of a multidisciplinary research approach and build arguments to synthesise the findings. This would be very important to the advocation of a pluralistic epistemology.

2.1 Psychology: Human Performance and Usability

The concept of Human Machine Interaction (HMI) can be traced back to the first time a human interacted with a "device" to make sense of its surroundings (e.g., a hammer or a compass). The general research topics in HMI have been developed or evolved to derivative themes that have drawn significant attention in the last several decades, such as Human Computer Interaction (Carroll, 1997; Dix, Finlay, Abowd, & Beale, 2003; Norman & Draper, 1986), Human Automation Interaction (Endsley, 2016b; Hancock et al., 2013; Kaber, 2017; Sheridan & Parasuraman, 2005) or Human Robot Interaction (Burke, Murphy, Rogers, Lumelsky, & Scholtz, 2004; Kosuge & Hirata, 2004; Sheridan, 2016). Although the artefacts are designed with different levels of intelligence and function complexities, the fundamental interactive formalities between human and artefacts, “the interaction and communication between human users and a machine, dynamic technical system, via a Human Machine Interface” (Johannsen, 2007, p. 132)”, remains essentially unchanged over the years - the dominating semiotics in HCI is a dyadic framework (i.e., machine presents signs and humans act upon them) that originated with Saussure (Flach, 2015).

The information processing cognitive psychology has been the key to HCI research (Card et al., 1983) to deal with the human limitations and usability issues. Part of the reasons is that historically humans were being viewed as systems with limited-capacity for information processing and stimuli compete for the resources (Broadbent, 1958). With the conventional belief that the meaning can only be structured from the inside of the human agent (so that the user’s mind is the only cognitive substance in the dyadic Human-Machine relationship), the HCI or HMI has been widely recognised as a fundamentally information processing task (Proctor & Vu, 2003) in which process the “bottlenecks” of information processing has drawn much attention in research. One well-known issue about this was “the Gulf of Execution” and “the Gulf of Evaluation” (Norman, 2013) situated in the classic HMI/HCI model (see Figure 3), which respectively reflect “the difference between what the user wants to do and what can actually be done using controls that are available”, and “the mismatch between the user’s intention and expectation and the actual state of the system” (Faulkner, 2000, p. 81). These are essentially addressing the discrepancy between the user’s inside world and external outside world (artefact) and such approaches are fundamentally rooted in the information processing cognitive psychology with strong implications about usability improvement. These might work well for systems that do not consider context of use like word processing software programme, but the underlying ontological assumption has significant limitations for addressing the design issues in a complex working context. These will be further clarified in section of 2.2 and 2.3.

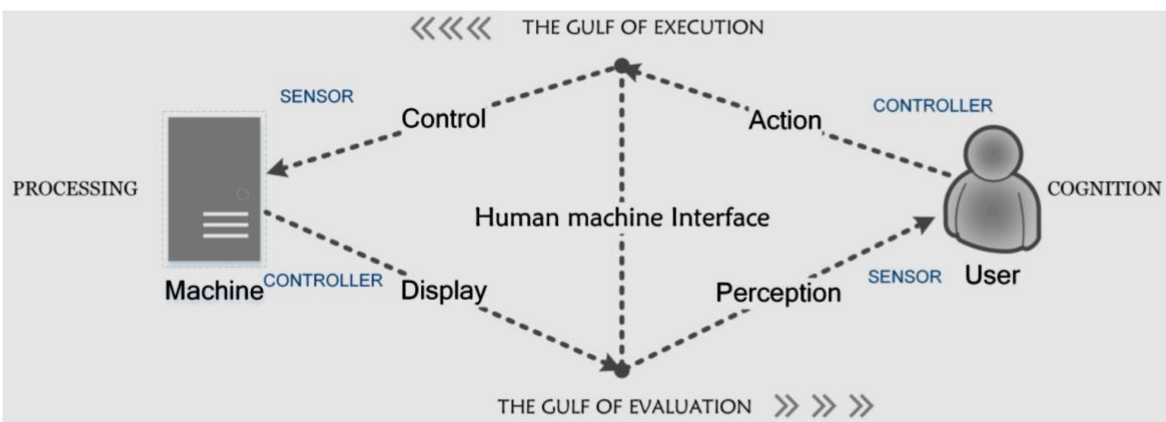

Figure 3. Classic HMI/HCI model (conceptualized from the work of Maldonado and Bonsiepe (1964) and Norman (2013)).

In fact the human’s cognitive systems and the mechanisms about information processing has been extensively exploited via different systematic approaches, looking at vision and attention (Eriksen & St. James, 1986; Kahneman, 1973; Posner, 1980), mental models (Craik, 1943; Johnson-Laird, 1983), memory functions (Baddeley, 1986), workload (Parasuraman & Hancock, 2001; Reid & Nygren, 1988), situation awareness (Endsley, 1995a, 1995b) and other human performance constructs in different human information processing stages (Carroll, 1997; Proctor & Vu, 2003; Wickens, 1992).

2.1.1 Selective Attention

A very important construct in information perception is attention, although there are no generally recognised answers about what attention is. One best known description on attention might be from James (1890) in his book *The Principles of Psychology* that "everyone knows what attention is. It is taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thoughts". There existed many theories that were trying to account for attention and elucidate what it really is, such as being conceptualized by as a spotlight which spatially disengages from current location, move to the target location and engage at the cue (Posner, 1980), or as a zoom lens that can allocate attention over a variable area so that saccades are directed to the geometric centre of the cues (Eriksen & Murphy, 1987; Eriksen & St. James, 1986), or be characterized with a selective filter in the *early selection* model (Broadbent, 1958), or be related to perceptual memory in the *late selection* model (Duncan, 1980), or developing hybrid models (Treisman, 1985) or Feature Integration Theory that assumes that the feature of stimulus are coded into a feature map for visual search tasks (Treisman & Gelade, 1980). Regardless of metaphors or models being developed or used, attention was widely recognised as a selective process that brings stimulus into consciousness or selects parts of visual items for further detailed analysis (Carrasco, 2011; Findlay & Gilchrist, 2003; Wickens, 1992). The core idea of this selectivity is that it reduces the information (Tsotsos, Itti, & Rees, 2005) while it provides "energy" to various information processing stages (Wickens, 1992), given that the supplies of the attentional resources is limited (Kahneman, 1973). The selection "efficacy" can be influenced by multiple factors, primarily in the two main forms of attentional selection that operate in parallel, bottom-up and top-down (Koch, 2004). In the bottom-up framework, salient object can easily directs and attract attention as if the selection is explicitly controlled by a salient map, influenced by the colour, orientation or conspicuity or feature contrast in the context (Itti & Koch, 2001). The top-down attention is driven by the task goals and it is under volitional control (Koch, 2004).

2.1.2 Situation Awareness

While attention is critical for perception, the central issues for information processing are about understanding the meanings of information and ongoing situations, which are related to a series of cognitive mechanisms. For example, mental models are created as "small-scale models" to represent external reality (Craik, 1943), conceptualised as a result of the physiological perception (Marr, 1982) or a representation of the world and their meanings and knowledge (Johnson-Laird, 1983). It enables a simulation of events that can support reasoning (Johnson-Laird, 1980; Johnson-Laird, 2008, 2010). In various definitions and understandings of mental models, a pragmatic perspective proposed by Rouse and Morris (1986) to emphasise its utility for understanding and improving system design has very important influences for the development of the theory of Situation Awareness (SA), which is positioned to address the essential questions about how we understand and interpret things. For example, "people use a process called pattern matching to link cues taken in from the current situation to schemata to pick the best match from those available" (p. 22) and "rapid classify and understand information perceived " (p. 23) (Endsley, 2011).

For the past 25 years SA has been one of the most popular framework models in cognitive science that is grounded on the information processing cognitive psychology and encompasses many cognitive constructs (Wickens, 1992). It has an extensive use and theoretical discussions in various sectors, mostly aviation industry (Riley et al., 2008; Salmon et al., 2008; Wickens, 2008). SA has some roots in the everyday language about explaining what the operator is (not) aware of what makes him/her get (lose) the "big picture". A critical assumption of this understanding is that operators must be aware of particular information at critical moments to make critical decisions (Lundberg, 2015). Thus, SA in this common usage, has been generally interpreted as something situated in the cognition of an operator. One example is that many references of SA in accident reports or academic research are largely associated with perceptual factors instead of system factors (Samantha, Steven, & Hyo-Sang, 2011; Selcon, Taylor, & Koritsas, 1991).

Endsley (1995a, 1995b)'s model of SA is one of the most widely referenced SA models. In her model, SA means an operator's knowledge of the environment at a given point of time (Endsley, 1995a, 1995b). It was defined as three levels of concept - "the perception of the elements in the environment within a volume of time and space (level 1 SA, perception), the comprehension of their meaning (level 2 SA, comprehension) and the projection of their status into the future (level 3 SA, projection/anticipation)". This notion of SA is considered primarily applicable in dynamic situations by Wickens (2008). Even its criticizers, such as Stanton, Salmon, and Walker (2015), also admitted that Endsley's contribution has "raise(d) the general consciousness to the idea of SA than any single article before or since" (p. 44). The central constituents in Endsley's model are goals, mental models, and situation model (i.e., levels of SA) (Endsley, 2000), coming along with the foundational concept of "meaning" in SA (Endsley, 2015). This is because knowing information of what is going on is implicitly suggesting the relevance of the goals and knowledge about perceived elements (a dynamic understanding of how the world works, i.e., mental model). To better solve the problems regarding the constraints in the context, the goal-directed task analysis was developed as alternative to cognitive task analysis (Endsley, 2011). A combination of a bottom-up data-driven approach (how a salient cue gets the operator's attention and directs changes of mental models) and a top-down goal-driven approach (how the goal directs the selection of mental models to direct attention) form the essentials of Endsley's model of SA (Endsley, 1995b, 2000, 2015). The underlying cognitive constructs also remain important in explaining how SA is formed and maintained in cooperative activities, such as a shared mental model contributing to a shared projection (Team SA) that concerns the team's understanding of the situation and corresponding decision making process (Endsley, 2015).

Endsley's model of SA is framed in terms of product, a state of knowledge (Endsley, 1995b, 2000), which in a sense separates itself from the interaction process in which it gets updated, although Endsley (2015) tried to accentuate the reciprocal relationship between the process and product. A consequence is that the substantial body of research that applies Endsley's model would use SA to refer to what people think in the prevalent context of assessment of one's awareness of the surrounding circumstances in search of accidents' causes or design improvement (Grech, 2008; Riley et al., 2008; Samantha et al., 2011). This leads to the caution of using SA as the causal agent (Flach, 1995b) or discussions around the "danger" of losing SA (Dekker, 2004; Dekker, 2015). The way Endsley structured and framed it in 1995 was shaping an representation of SA that it lacks the ability to account for the "system part" (Salmon et al., 2008; Salmon, Stanton, & Young, 2011; Sorensen, Stanton, & Banks, 2011; Stanton et al., 2015; Stanton, Salmon, Walker, & Jenkins, 2009), which to some degree is the case considering her views in 2015 have evolved (Klein, 2015).

The human mind creates a cognitive scheme of the world and directs their actions to look for the anticipated aspects of the information. The sampled results from the world would in return modify and update the internal cognitive map. The concerns on how knowledge is maintained in a changing environment through cyclic cognitive processes are essentially connected to the perceptual cycle model proposed by Neisser (1976), which has inspired a lot of other research regarding the SA conceptualisation (Adams, Tenney, & Pew, 1995; Salmon et al., 2008; Smith & Hancock, 1995;

Stanton, Salmon, Walker, Baber, & Jenkins, 2006; Stanton et al., 2009). The outstanding idea is that SA is both product and process (Smith & Hancock, 1995) and thus it is the interaction and coordination of the systems that shall be of concern (Sorensen et al., 2011; Stanton, Salmon, et al., 2006). The concept of Distributed SA proposed by Stanton, Stewart, et al. (2006) certainly expanded the scope of SA from cognitive psychology to the sociotechnical system's level. In contrast with Endsley and Jones (2001)'s concept that "awareness" is not applicable to an inanimate machine (because SA distributed in the system was meaningless unless the operator was aware of the information and made sense of it in an accurate way at the right time), Distributed SA described SA as an emergent system property residing in all of the involved agents, influenced by Hutchins (1995)'s distributed cognition (Stanton, Stewart, et al., 2006). These are perhaps incompatible conceptualizations of SA comparing to Endsley's model, but there is not necessarily a right or wrong one.

Human cognition about how people understand and form meanings is still an important part of a sociotechnical system, which does bring certain value to research on SA. For this thesis, Endsley's model of SA was used in various studies from the angle of psychology to explore how the introduction of advanced technologies could impact perception, understandability and decision making. This does not mean Ensley's approach is perfect or show the author's positions towards design and use of technology are bounded to cognitive information processing psychology (e.g., design something good to counter the human limitations). Nevertheless, the use of SA and its reflections in corresponding studies may evolve thoughts to go beyond the displinary boundary and synthesise connections between different dimensions into a coordinated and coherent whole later on. One example for SA is that it allows us to reflect upon inseparability of situations and awareness (Flach, 1995b) and meanings from an ecological perspective (Flach, Feufel, Reynolds, Parker, & Kellogg, 2017; Minotra & Burns, 2015). This may imply an evolving direction in which disciplinary knowledge could be integrated or harmonized in future interdisciplinary research.

2.1.3 Decision Making and Human Errors

Decision making is about problem solving, a search for a path that connects the initial state and the goal state (Proctor & Vu, 2003). Such search processes have traditionally been segmented. In the traditional information processing model, decision making is a critical step in the seemingly linear process of information handling (i.e., sensory processing, perception, decision selection, response execution) affected by memory and attentional resources (Wickens, 1992). Simon (1957) argued that three activities were involved in decision making: Human need to find or identify the situation, and then invent, develop and analyse possible alternatives, and finally select a specific path from those available. Rationality is the implicit word behind the segmentation of the processes and logically sound decisions are what a rational decision maker seeks after, though the degree of rationality can vary (Supe, 1969). The traditional models are usually associated with laboratory experimental approaches, proving testing and formalization. The core assumption about rationality in decision making is that objective data and formal process of analysis empowered by the laws of probability, expecting utility theory or Bayesian statistics to yield optimal judgements (Polič, 2009). However, there are many critics about the rational decision making approach such as cognitive resource limitations and behaviour biases (Kørnøv & Thissen, 2000). Other alternative theories stemmed from the rational decision making models were proposed, such as Bounded Rationality (Simon, 1955) and Prospect Theory (Kahneman & Tversky, 1979). In the discussion of information processing and rationality, "human error" is frequently mentioned as a failure of rationality. It can refer to slips, lapses, and mistakes (Reason, 1990). For example, an operator can make a decision intuitively, but the decision may be a mistake. Wickens (1992) argued the problem is not at action execution but situation assessment or planning and the problem of lapses is related to memory failures.

Heuristics and experience are frequently mentioned as useful approaches to constrain search and thus enable rapid responses in decision making (Kahneman & Tversky, 2000; Klein, 1993; Proctor & Vu, 2003). It indicates that humans do not necessarily adhere to the classic optimal decision making process driven by rationality or probability in many situations. One well-known example is that firefighters were found that they did not make algorithmic strategies or comparing alternatives at critical moments, but they just simply recognised the situation with experience and used adaptive ways to put out fires (Klein, 1993). The Data-Frame model (Klein, Phillips, Rall, & Peluso, 2007) reflects a cognitive mechanism under dynamic situations that is seemingly consistent with the proposition of "learning by doing" (Flach et al., 2017) or the dynamics of assimilation and accommodation (Piaget & Inhelder, 1969). The big picture is that, since the 80s, much research focus has shifted from laboratory settings to dynamic natural settings to study how people actually make decisions in complex tasks, leading to the emergence of situated cognition (Suchman, 2007), distributed cognition (Hutchins, 1995), recognition-primed decision making under the framework of naturalistic decision making (Klein, 1993, 1997) as examples. Flach et al. (2017) suggested that the perceptual processes associated with formulating problems, generating hypotheses and triggering right actions are the key factors that can shape the performance variance among experts and novice, which those laboratory-based studies account for little. In addition to these models, emotional components were also found to play important roles to trigger actions (Damasio, 1994).

In the decision making process, people may recognise the situation very fast or need to spend deliberative efforts to diagnose the problem. Some research suggests the existence of two (independent) systems of decision making: one is fast and intuitive and one is slow and analytical (Kahneman, 2011). Flach et al. (2017) argued that the qualitative difference in experience is a result of situation awareness as the coordination between the two systems and the underlying perception-action process is still one single "muddling" dynamic process. This muddling through process is an indication to reveal the dynamics in decision making or to reflect the process of "leaning while doing". Though many lab-based experiments looking at psychological factors may still be useful to probe what went wrong to lead people to make "bad" decisions, they usually do not capture the context in which how decisions were made in reality. For instance, decisions made at a given moment which made perfect sense for that particular context could be revealed their vulnerability by hindsight (Dekker, 2004).

2.1.4 Usability

The central role of psychology in HCI is that that it produces guidelines for developers and helps to verify the usability of the systems. As Carroll (1997) described, "software psychology inaugurated a variety of technical projects pertaining to what we now call the *usability* of systems and software" (p. 502). Usability is about the ease of using or "user friendliness". It can be traced back to the time of World War II when people want to define a job that suits anyone instead of finding someone specific to do the job (Kortum, 2016). After the war, the usability was introduced to a wider range of industrial arenas, where it was mostly related to safety and health care since the 70s. A well-known accident was the nuclear accident at Three Mile Island. At that time, experts believed that better training would have prevented the problem and avoid future, similar events (Perrow, 1984). More recent accidents were the grounding of the Royal Majesty thought to have been a result of navigators failing to notice the crucial codes on the display (Lützhöft & Dekker,

2002) and the crash of Airbus 320 because the pilot turned off the flight safety systems (Casey, 1998). The emergence of the industrial accidents in tandem with the rise of personal computers since the '80s has brought usability to unprecedented attention.

Nielsen (1993) framed usability under the overarching umbrella of system acceptability, which is concerned with whether the system is suitable to meet the needs and requirements from the users' perspective. Usefulness is composed of utility and usability, where utility is a question that the functionality can serve the needs and usability is a question of how well the users can use that functionality, including how easy it is to learn and remember, how efficient it is to use and the level of subjective satisfaction (Nielsen, 1993). Compared to Nelsen's definition, the definition provided by the International Organization for Standardisation (ISO), ISO 9241-11, is directed to a process-oriented approach to understand usability by accentuating context-of-use during specification, design and usability evaluation (Abran, Khelifi, Suryn, & Seffah, 2003; ISO/IEC, 2001). ISO 9241-11 defines that "software is usable when it allows the users to execute the tasks effectively (in terms of how well the product can meet the needs of the task), efficiently (in terms of how much resources are required for accomplishing task) and with satisfaction (in terms of how favourably users respond to the product) in the specified *context of use*". However it does not show the learnability characteristic as recommended by many other standards and experts on usability (Frøkjær, Hertzum, & Hornbæk, 2000; Kortum, 2016; Stanton, Salmon, et al., 2006). In addition, a crucial aspect is missing in this definition which is much appreciated by many domain experts, i.e., how much impact the artefact can have on safety or security. While good usability may be invisible, poor usability usually can be noticed and in some cases can lead to severe consequences (Casey, 1998). To safety-critical industries like shipping, this is an important aspect to consider in usability evaluation.

The goal of usability evaluation is to improve the product and minimize the negative consequences by reducing "human errors", increasing user efficiency, increasing the user's and system's safety and increasing user satisfaction (Kortum, 2016). The usability assessment is tightly connected to the interface analysis methods (Stanton, Salmon, et al., 2006). One main approach is to look at the performance of the user under controlled conditions and their internal state (psycho or psychophysiological measures) (MacKenzie, 2012), as these can reflect the extent of ease of use (Bevan, Kirakowski, & Maissel, 1991). Commonly used techniques include software usability measurement inventory (Kirakowski, 1996), the Quality In Use Scoring Scale (QIUSS) (Sherwood-Jones, 2008), etc. Another approach is to use task and link analyses to describe and represent how an activity of interest is performed with the interaction of the interfaces and evaluate the usability (Stanton, Salmon, et al., 2006). For example, the researchers can focus on the physical aspects of the interfaces, such as the interface survey methods to consider the aspects of controls and displays, labelling, coding consistency (Kirwan & Ainsworth, 1992), or focus on the relationship between interface components to probe and identify the extent of importance of these links, such as the link analysis (Sears, 1993).

2.2 Sociology: Activities and Context

The applied psychology of HCI is largely theoretically based on information processing psychology (Card et al., 1983). The research on perception, SA, usability and other related areas are very important to HCI (a sort of applied cognitive science study from this perspective) as they basically aim to "apply what is known from science to the design and construction of machines" (Norman, 1983, p. 31). For example a plethora of research has been dedicated to exploring the usability issues in the ill-designed computer interfaces in terms of how they failed to support the human information processing capabilities or accommodate the human's intrinsic limitations (Dumas & Salzman, 2006; Faulkner, 2000; Hollingsed & Novick, 2007). While HCI was concerned about studying individuals in isolation from the surrounding environment and context, there has been a growing consensus in academia since the '80s that the cognitive paradigm has its own limitations and there shall be more room for social and contextual orientation (Carroll, 1997). This section will present pertinent social constructs that shed light on the context of technology use.

2.2.1 Activity Theory

2.2.1.1 Concepts and Developments

Activity Theory is a social theory of human consciousness based upon anthropological / psychological theory of Vygotsky (1978) and Leont'ev (1978) that concentrates on the interactions between humans and artefacts in natural every-day life settings (Bødker, 1990; Kaptelinin & Nardi, 2006). Activity Theory is not about studying isolated individuals, but to use an analysis of structure and processes of activities to understand individual human beings and the social entities they compose. Vygotsky (1978)'s theory about the relationship between "the mind" and the society informed that subjects are intrinsically social and "the mind" is embedded in the interaction between human beings and the world. That is to say, consciousness is reflected and manifested by what humans do in the social environment (Kaptelinin & Nardi, 2006). Activity Theory provides a very general philosophical framework for understanding the human culture, totality of human work, praxis (i.e., the ways of doing work), organisational development and design (Bødker, 1990; Kuutti, 1995).

The basic representation of activity is the existence of subject (a person or a group), object (an objective that motivates the activity) and the purposeful interactions between them (Leont'ev, 1978). Activity Theory advocates that it is the activity that bridges subjects and objects so that activity maintains the properties of subjects and objects and also influences the development of the subject and the object (Kaptelinin & Nardi, 2006).

The framework of Activity Theory has a long history on the concept development of activity. The recognition of activity can stem from the philosophical debate around Kant, Fichte and Hegel's idealism versus Feuerbach's materialism, and from Marx and Engels (1845)'s dialectical materialism and Vygotsky (1934)'s soviet cultural-historical psychology developed in Russia from 1920s to 1930s. Vygotsky (1934)'s work reflected a thought that was consistent with the dialectical materialism's "social being determines consciousness", that human mind does not exist independently but there is a social nature about it - our behaviours are constantly shaped by the culture, by the environment, by the language, or by the context in which we are interacting with the world. The subjects and objects are people and entities developed in culture and are essentially social, therefore the social activities are chosen as the unit of analysis for psychological research. This was believed to be a radical deviation from the typical empirical studies in psychology that at time focused on subjective and objective phenomena in observations and controlled experiments (Kaptelinin & Nardi, 2006). Vygotsky proposed that it was necessary to study the fundamental part of the phenomenon through cultural and social lens to understand the development processes, the nature of consciousness and mind (Vygotsky, 1962, 1978). If the classic analytical approach is about studying the subjects and objects separately in an attempt to find some relationship in between, then Vygotsky's theories are looking at the interactions or the "acting of the world". Intervention is even considered as necessary to understand the essence of the phenomenon or the development processes, which is also in sharp contrast with the traditional research positions in controlled experiments.

One instance to illustrate how Vygotsky illustrated the dynamics between individual and social/community is the concept of the “zone of proximal development”, which is about evaluation of the development of individuals (Vygotsky, 1978). Vygotsky deemed that it was not meaningful to use the current performance to determine the development level, unless the “distance” (i.e., improved performance) between what the an individual could do alone and what an individual could do once he/she was given support from others or collaborated with others was improved (Vygotsky, 1978). The concept of “proximal development” is based on the conception that “new functions emerges first as distributed between the individual and the social environment” (inter-psychological), and then “become appropriated by individuals (intra-psychological)” (Kaptelinin & Nardi, 2006, p. 59). This essentially addresses the mind’s social-cultural origin (Kaptelinin & Nardi, 2006).

These concepts brought significant contributions to the development of cultural-historical psychology and were further expanded to the Activity Theory by Aleksey Leontiev. Leontiev focused on the evolution of mind and introduced the concept “activity” as an analytical tool to understand the fundamental subject-object interaction (Leont'ev, 1981). The “activity” in a contemporary sense is framed as a basic unit of analysis which scaffolds the minimal meaningful context for individual actions (Kuutti, 1995) or “non-additive unit of the corporeal, material life of the material subject.” (Leont'ev, 1978, p. 3). The hierarchical structure of an activity provides an account for the interactions at multiple levels of acting in the world (see Figure 4).

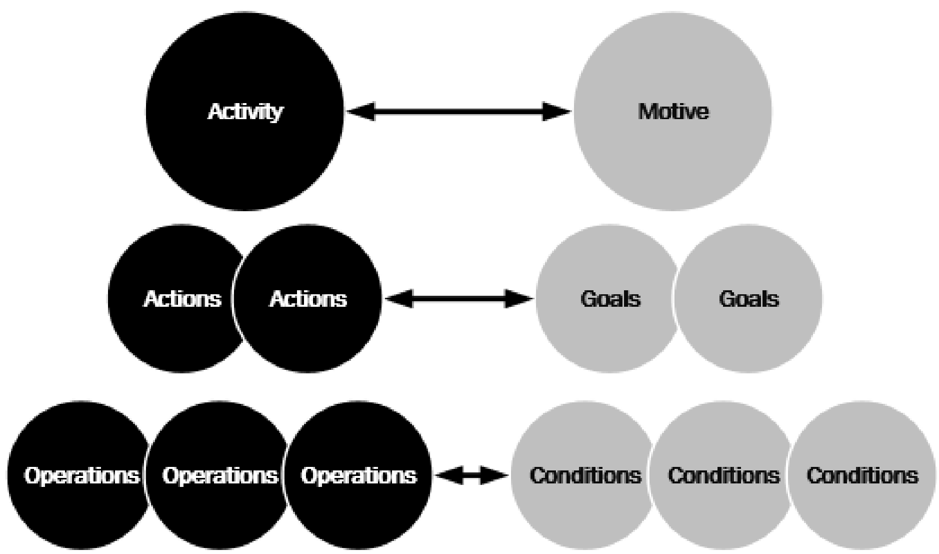

Figure 4. The hierarchy of activity.

What fundamentally differs one activity from another activity is the object of activity, or a “motive” (Leont'ev, 1978). Human activities are directed towards objects associated with all kinds of needs. For example, a navigator conducts ship-handling in a safe manner (activity) because of the safety concerns (motives). The conflictions can rise in the activities characterised with different objects that can be transformed in the course of an activity (Nardi, 1995). An activity is composed of a sequence of steps, i.e., actions. People consciously take actions to achieve the goals and the goals direct actions. For example, a navigator wants to achieve the goal of collision avoidance, so he needs to take actions to change the course or the speed if necessary. Each action process is then decomposed into a sequence of lower-level steps, i.e., operations. For example, the navigator needs to monitor the ECDIS (Electronic Chart Display and Information System) and radar systems and control the ship's throttle. Operations are oriented towards the conditions under which subjects is trying to attain a goal (Kaptelinin & Nardi, 2006). The key point is that the constituents of activity are not fixed but they can dynamically change as conditions change (Nardi, 1995). That is, the change of the context can re-allocate the constituents of an activity.

Vygotsky and Leontiev's research have shaped a new perspective that activities are not treated as a collection of a linear movement but should be analysed through dynamic lenses grounded in cultural and historical developments. By that time these researches mainly focused on individual's activities in the social environment under the subject-object interaction framework. Later the scope has been further expanded to collective activities with a triadic model, i.e., subject-object-community (Engeström, 1987, 1999): Engeström (1987) used a notion of "community" and its relations to subject and object to illustrate the relationship between individual and group (e.g., social norms, culture, rules, and conventions) and the relationship between group and organisation (e.g., division of labour). Generally, the studies about collective activities further enrich the content and scope of Activity Theory.

2.2.1.2 Influence on HCI

As introduced in previous chapters, there was a tight coupling between cognitive psychology and interaction design in early 80s, that HCI researchers usually established an hypothesis, formal user models and conduct controlled experiments to measure the effectiveness of the interfaces in terms of how they would influence human cognition in a specified task (Carroll, 1997; MacKenzie, 2012). The dominant paradigm for HCI was information processing with a low-level unit of analysis on user-interface interaction, so the research aimed to discover empirical evidences to suggest designs that can facilitate the accomplishment of a task (Wickens, 1992).

The limitations of this approach became well-known in the mid-90s as it de-emphasises the role of context, the meaningful properties of the user's interaction and the desires of users (Hutchins, 1995; Suchman, 2007), but what really allows Activity Theory to be considered as a foundation in HCI starts from Bødker's work in interface design research (Bødker, 1991). Bødker (1990) realized the limitations of employing exclusively an information processing paradigm in HCI research and pointed out that there was a gap between organisations and system design in many real-life design projects. That is, design organisation did not have skills or techniques to address the growing demands upon them with the advent of advanced technology. Instead, it would likely bring more challenges - "if the organisation is not considered in together with the artefact, one may introduce new contradictions…" (p. 6). Bødker (1990) proposed to employ Activity Theory to consider all aspects of activity, from motivation to operations, to address the issues in organisational change and systems design. The idea is to use Activity Theory to understand how operations, actions, and activities are woven into systems design as well as the physical and social conditions of an activity that determine how the operations are carried out from a holistic perspective. The artefact shall no more be seen as a pole but "a potential mediator of the use activity" (p. 8) and the meaningful context in which the activity occurs needs to be included in the analysis. By considering the human use of technology within a much wider context of human interaction with the world, this perspective expands the scope of traditional HCI significantly (Kaptelinin & Nardi, 2006; Kuutti, 1995).

Notably this notion of mediation has been underpinning the need for Activity Theory to be the foundation of HCI (Kaptelinin & Nardi, 2012; Kuutti, 1995). It changes how researchers used to understand the artefacts' role in HCI. Artefacts can shape how we interact with the world and they may also represent how we understand the world. The culturally developed artefacts may become parts of what humans are (Flach & Voorhorst, 2016; Pirsig, 1974), or "as integral and inseparable components of human functioning" (Engeström, 1999). They are "the fundamental mediators of purposeful human actions that related human beings to the immediately present objective world and to human culture and history" (Kaptelinin & Nardi, 2006, p. 71). An activity becomes a form of doing directly to an object. The subject uses the technological artefacts in a certain context with attentions and motives and the artefacts' roles are mediating the relationship between the subject and the object of that activity. Different activities have different objects that can be transformed to outcomes to motivate the existence of an activity (Kuutti, 1995). A mediated relationship between the user (as the subject) and instantiating motives (as the object) can be exemplified as how an operator uses computers to monitor status changes in an automation system. The meanings of such a behaviour in the activity are embodied in the use of the mediating artefacts.

In terms of interface design, there is one important concept that has been influenced on the Activity Theory approach – affordance. It is a concept proposed by Gibson (1979) in an ecological approach to perceive the world. The notion of affordance was introduced to HCI as a means to enhance the usability, as it essentially provides a property of interaction to indicate "actions possibilities" or "clues to operations" (Norman, 2013). Gibson (1979)'s views on affordance do share some similarities with the Activity Theory that possibilities for actions are impacted by the context (Kaptelinin & Nardi, 2006), however, its HCI applications are typically limited to low-level manipulations acted upon the interfaces, which corresponds to the operation level in the hierarchical structure of activity (see Figure 4). Bærentsen and Trettvik (2002) argued this was primarily because Gibson's notion had been mainly interpreted from the perceptual perspective in the field of HCI, "leaving the activity of the organism as a largely implicit precondition" (p. 51). Therefore Activity Theory was proposed to be a frame of reference to further extend the notion of affordance to the level of actions and human activity (Bærentsen & Trettvik, 2002). In addition, Activity Theory also motivates the HCI researchers to concern on the difference between "interface" and "domain". One example is the concept of direct manipulation, which is proposed by Shneiderman (1983) about the interface design improvement. The important mediation relationship informed by Activity Theory addresses the concern that there is a difference between "interaction instruments" that the user is manipulating directly and "domain objects" that the user is manipulating indirectly (Kaptelinin & Nardi, 2006). The user interfaces are not just concerned about physical aspects or logical interactive process, but also about how "interaction instruments" on the display are relevant to the "domain objects" (Bødker, 1990, 1991; Kaptelinin & Nardi, 2006). This notion shares many similarities with the ecological interface design (Bennett & Flach, 2011; Vicente & Rasmussen, 1992).

The influence on HCI is also beyond the interface design, as the activity-theoretical insights provide a wider context to recognise real human activities in the field and therefore new perspectives on system design which is not grounded on the normative description of work. The real-world activities are intertwined with different sets of tools, intricate sets of social norms and rules, and various means of organizing communities (Engeström, 1999). Within the community of Computer Supported Cooperative Work (CSCW), many studies have been conducted based on the Activity Theory approach (Bardram, 1997; Kuutti, 1991, 1999; Nardi, Whittaker, & Schwarz, 2002; Zager, 2002), providing insights not only about design but also about knowledge production and management in organisations. In addition, Activity Theory was also employed in the Computer-Supported Collaborative Learning (CSCL) research, which was tightly connected to the learning science that was concerned with studying how people can learn together with the help of computers (Koschmann, 1996; Stahl, Koschmann, & Suthers, 2006). For example, based on the assumption that activity is mediated by cultural tools and conceptualized on multiple levels, and the conceptual understandings were first established socially, Gifford and Enyedy (1999) proposed the Activity Centred Design (ACD) to meet CSCL needs.

One important lesson the research domain of human factors and interaction design for the past twenty years is that context matters (Flach, 2015; Kaptelinin & Nardi, 2006; Nardi, 1996). Context is the activity itself, constituted through the enactment of an activity involving people and artefacts; context is both something internal (e.g., motivation) and something external (e.g., other people, artefacts, environment, settings) (Nardi, 1995). The notion of context from Activity Theory became central to the development of HCI. Over the years all these activity-theoretical insights have significantly enriched the original framework of Activity Theory but more importantly, they substantially extend the scope of traditional HCI with the information-processing-based psychological approach that is introduced in the preceding section. Table 1 provides an analytical summary of these theoretical presentations.

Table 1. Traditional HCI with the information-processing-based psychological approach vs. modern HCI with the social-cultural approach.

	TRADITIONAL HCI	**MODERN HCI**
DOMINATING FACTORS	Psychological factors	Social and cultural factors
UNIT OF ANALYSIS	Low-level analysis on user-interface interaction	High-level analysis on meaningful activity
CONTEXT	User-Tool	User-Tool-Environment
MAIN FOCUS	Tasks (typically individual)	Mediating artefacts in subject-object relationship (typically collective)
METHODS	Laboratory studies	Ethnographic studies focusing on practices in real-life
APPROACHES	Normative such as task analysis	Descriptive approach such as Activity Theory
INCLUSIVE NOTION	Affordance, etc.	CSCW, CSCL, etc.

2.2.2 Situated Action and Distributed Cognition

The approaches of situated action (Lave & Wenger, 1991; Suchman, 2007) and distributed cognition (Hollan, Hutchins, & Kirsh, 2000; Hutchins, 1995) also advocated to study and understand the actual behaviours in real-life settings and emphasised the importance of context.

Situated Action focuses on "emergent property of moment-by-moment interactions between actors and the environment of their action" (Suchman, 2007, p. 177). The key notion of situated action is "situatedness" in a real setting as opposed "rationality" embedded in the traditional information processing paradigm, which Suchman (2007) explained as follows: "Every course of action depends in essential ways on its material and social circumstances. Rather than attempting to abstract action away from its circumstances and representing it as a rational plan, the approach is to study how people use their circumstances to achieve intelligent actions. Rather than building a theory of action out of a theory of plans, the aim is to investigate how people produce and find evidence for plans in the course of situated action. More generally, rather than subsuming the details of action under the study of plans, plans are subsumed by the larger problem of situated action" (p. 70).

The analysis unit of situated action is "the activity of persons-acting in setting" (Lave, 1988), that is, the relation between the individual and the environment. But what makes it different with Activity Theory is that it emphasises much more on personal improvisation and accounts for the temporal sequencing of responses to contingency while Activity Theory offers a more comprehensive framework to investigate a more durable and stable phenomena that persists across situations (Nardi, 1995). Situated action argues that the context can influence the activity, so people can improvise and innovate based on the specific situation, whereas the traditional information processing paradigm asserts that problem solving is a process characterized of rationality (Lave, 1988). For example, learning at work is essentially a both culturally and socially situated activity (Leidner & Jarvenpaa, 1995). In Lave and Wenger (1991)'s concept in *communities of practice*, groups of workers share a common concern and learn how to improve the ways of doing as the interaction between and within the groups proceeds on a regular basis. Knowledge development is seen as collective and collaborative achievements in the communities of practice (Lave & Wenger, 1991; Lundin, 2005; Orr, 1996). The emphasis is to situate learning as "an emerging property of whole persons' legitimate peripheral participation in communities of practice" (p. 63) and reflect "the interdependency of agent and world, activity, meaning, cognition, learning and knowing" (p. 67) – that is to say, knowledge development is achieved by increased participation, which refers to the process in which a "newcomer" immerses himself or herself in the sociocultural practices of a community and thus his/her competence would grow as he/she is more knowledgably skilful through more interactions (Lave & Wenger, 1991). The benefit is that the characteristics of situatedness can breed collaborations and innovations through the participation of multiple agents (Wenger, 1998; Wenger, McDermott, & Snyder, 2002).

The distributed cognition approach is to "understand the organisation of cognitive systems" and "extends the reach of what is considered cognitive beyond the individual to encompass interactions between people and with resources and materials in the environment" (Hollan et al., 2000, p. 175). It suggests that distributed cognition uses a cognitive system as the unit of analysis, but this cognitive system, to activity theorists, is a notion very similar to an activity (Nardi, 1995). Nevertheless, the key idea in distributed cognition is to direct away the analysis from individual properties or knowledge to a system level: the distributed collection of people and artefacts, the functional relationships of the system (Hollan et al., 2000). This is also opposed to the classic view of the information processing paradigm that we shall investigate how people think and what people know, or "something in the head". Distributed cognition is concerned with structure and representation inside and outside the head as well as the transformation these structures undergo (Nardi, 1995). For example, Hutchins (1995) observed the activities comprised of the navigators and the instruments as a cognitive system formed "in the wild", meaning much of cognition is not in the head but out in the real world.

When Activity Theory focuses on the importance of motive and consciousness, it also implies that human and artefacts are asymmetrical (Kaptelinin & Nardi, 2006). This is not how distributed cognition recognises the relationship between human and artefacts - it is concerned about the coordination between human and artefacts as they are conceptually equivalent agents (Nardi, 1995).

Although there are differences between distributed cognition and Activity Theory, Nardi (1995) argued that in principle they are very close in spirit and two approaches will mutually inform and even emerge overtime.

2.3 Ecology: Holism

The activity-theoretical research has informed us of the importance in considering the nature of the context in which action is embedded and the meaning of an object that can shape a person's understanding and direct his/her actions (Kaptelinin & Nardi, 2006; Leont'ev, 1978; Vygotsky, 1978). People work in a certain environment to use the technological artefacts to fulfil the work demands. Automation may have failures and humans may make mistakes (Bainbridge, 1983; Reason, 1990). It is increasingly important to realize the limitations of the man-machine dichotomy (Flach & Hoffman, 2003), which usually treats the elements in isolation from the other and draws attention within the traditional psychological approach dominated by the information processing paradigm. How to improve interface design with ecological concerns, how to integrate human-machine as a whole or to facilitate the development of an eco-system, gradually emerge as more important questions in modern HCI studies (Behymer & Flach, 2016; Bennett & Flach, 2011; Dekker, 2011; Endsley, 2016a; Hobbs, Adelstein, O'Hara, & Null, 2008). This section will present pertinent ecological constructs and introduce the literature about automation and the systems perspectives. Although the substantial work in this thesis has not been focused on how to use the ecological concepts to conduct interface design or work analysis, the author hopes the introduced literature could provide the relevant theoretical context to the readers to understand ecological implications of future research from the findings of the appended article.

2.3.1 An Ecological Approach

Brunswik (1952) framed the "Lens Model" to describe how a person perceives the environment and forms the representation of the world to address the significance of ecology in psychology. Taylor (1957) also proposed the necessity to understand the human-artefact system as a human-environment system in psychological research: "In many circumstances the behaviour of the man was inseparably confounded with that of the mechanical portions of his environment. This means that psychologists often could not study human behaviour apart from that of the physical and inanimate world" (p. 257). Gibson (1979) further formalized this thought and developed what Neisser (1990) described as "revolutionary psychology" – an ecological approach to analyse the environment and the adaptive relations between animals and their environment. These important and novel Gibsonian concepts are congruent with what Taylor (1957) described earlier that there is inseparability of the behaviour of the human from the physical environment, which means it is a radical departure from the traditional views of psychology as a study of the human organism (Heft, 1997).

The ecological approach promises a basic foundation to allow us to understand the issues in a HCI/HMI context via a human-environment system perspective (Flach, 1995a) and generates many implications not only in psychology but also in epistemology (Heft, 1997). From the epistemology's perspective, it was originally believed to be two sciences in which we understand the world – the matter in the wild and the mind in the head (Flach & Voorhorst, 2016). The ecological approach made the claim that it only has one unified science concerning the experience of the observer that his experience can only be understood from a perspective that consider interactions between mind and matter (Bennett & Flach, 2011; Flach & Voorhorst, 2016).

2.3.1.1 Ecological Interface Design

The ecological approach has significant influence on development of system-oriented theories and interface design in the field of HCI (Rasmussen, 1986; Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1992). Informed by the organism-environment reciprocity, the framework of Ecological Interface Design (EID) was proposed to address the design issues residing in the interaction between an operator and the controlled process in his/her work domain (Rasmussen & Vicente, 1989) (see Figure 5).

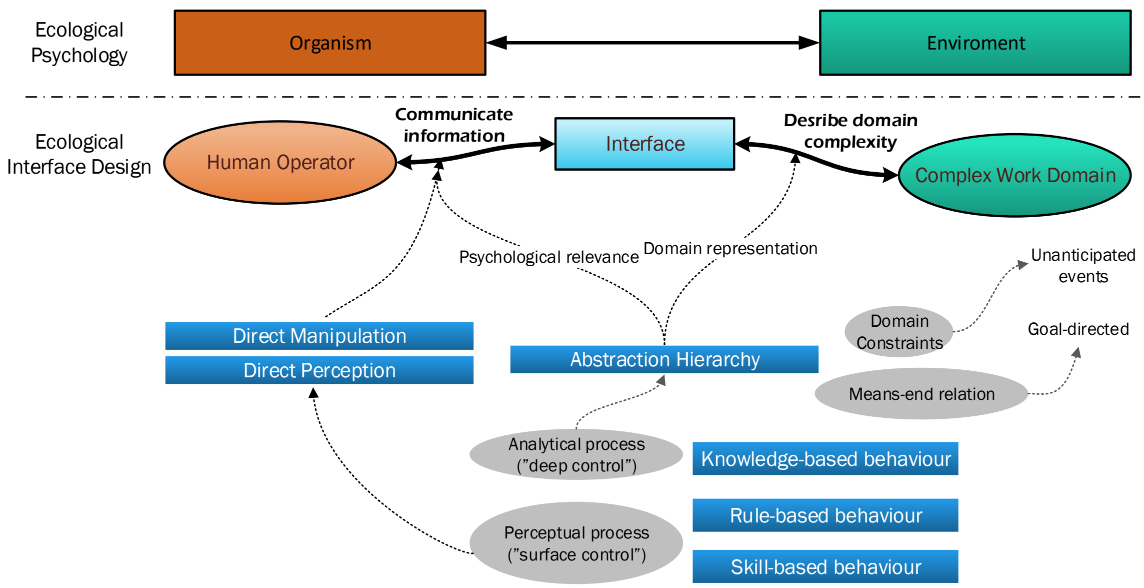

Figure 5. Ecological Interface Design framework and its underlying theoretical constructs, adapted from the models from Vicente and Rasmussen (1992) and Bennett and Flach (2011).

As the previous literature suggested, the traditional Interface Design (ID) had much to do with the human operator's information processing capacities in cognitive science and rational enumeration of the possible events in engineering. However, this has been increasingly seen as a limited solution to support the operators in complex sociotechnical systems (Rasmussen, 1986; Vicente & Rasmussen, 1992). One typical example is the Three Mile Island accident, as Perrow (1984) argued that as long as the system is complex and tightly coupled, then there would be unexpected, incomprehensible, uncontrollable and unavoidable accidents and failures. Human operators play the pivotal roles to influence the system's safety (Edwards, 1972; Hetherington et al., 2006) but human operators' mistakes can contribute to occurrence of the accidents, typically when they are confronted with unexpected events or unfamiliar situations (Rasmussen, 1969). It was found that the one of the key issues was that lack of functional relationship of the controlled process could make the interface provide incomplete problem representation (Rasmussen & Vicente, 1989; Smith, 1989), leading to undesired human performance. This is essentially a question of how to find a suitable language to describe the complexity of the domain, to reveal the constraints within and unravel the intricate relationship of the variables in the controlled process (Vicente & Rasmussen, 1992).

To address this issue, the EID framework takes the concept of Abstraction Hierarchy (AH) proposed by Rasmussen (1981) as one of its underlying theoretical constructs. AH employs a systematic approach to represent goal-related domain constraints on each level. These levels include: functional purpose (the overall purpose of the system), abstract function (the intended causal structure of the process in terms of mass, energy, information or value flows), general function (e.g., basic function, flow and storage of heat), physical function (status and characteristics of the components and their relationships), physical form (location and appearance of the components) (Rasmussen, 1981, 1986). The levels are linked with a means-end relation (Vicente & Rasmussen, 1992). The advantages of using AH is that it not only provides a goal-directed language to describe the problem spaces, functional relationships and domain constraints to form an information basis to cope with complexities (Flach & Voorhorst, 2016; Vicente, 1999), but enriches the problem solving protocols via manifesting some psychological relevance (Vicente & Rasmussen, 1992). The employment of AH as EID's underlying foundations is important for creating the representation to aid particularly knowledge-based behaviours (e.g., analytical problem solving), which is at the top level of the Skill, Rule and Knowledge (SRK) taxonomy developed by Rasmussen (1987).

EID also concerns the other central issue in ID: how the interface can communicate with the operators (Vicente & Rasmussen, 1992). Compared to analytical processing at the highest level of the SRK taxonomy, perceptual processing pertinent to the lower levels (i.e., rule- and skill-based behaviour) is more responsive and efficient (Flach et al., 2017; Kahneman, 2011; Vicente & Rasmussen, 1992), of which ID shall take advantage. EID proposes to create a mapping relationship between the invariants of the functional systems in the work domain and the interfaces on the display, to allow "direct manipulation" and "direct perception" (Bennett & Flach, 2011).

The concept of direct manipulation was originally coined by Shneiderman (1983) and further elaborated by Hutchins, Hollan, and Norman (1985) that this "directness" is a result of fewer cognitive resources spent in the process of accomplishing a task. Bennett and Flach (2011) use this term to refer to the objects in the interface that can be acted upon. Flach and Vicente (1989) framed the notion of direct perception based on the ecological insights from Gibson (1979), that is if there is a direct coupling relationship between perception and action in an organism-environment system, then ID should map the ecological constraints in the work domain or the invariants in the real world onto the displays. The design should create a virtual ecology in a way that the "affordance" (goal-directed action aids considering the work constraints) can be salient to the operator (Rasmussen & Vicente, 1990). EID intends to interpret the information symbolically in knowledge-based level and "display the process' rational structure directly to serve as an externalised mental model" in order to support learning adaption and decision making in complex systems (Rasmussen & Vicente, 1989, p. 530).

Affordance, the well-known ecological notion proposed by Gibson (1979), had a profound effect on cognitive psychology. Although affordance has generated other interpretations in the field of HCI (Norman, 2013), the concept here refers to an emergent property of the environment, i.e., "what it offers the animal" (Gibson, 1979). Gibson (1979) developed ecological physics to describe a worldview for studying perceptual experience which is no more independent of an observer, opposed to the classical physics which claimed that the properties of the objects are always observer independent (Flach, 1995b). A simple example is to describe a road as "walkable" rather than stating its absolute width and texture. The ecological approach asserted that the laws that relate the observer to the environment are something tightly connected to functional aspects of the environment, i.e., affordances (Flach, 1995b).

Affordance attempts to reveal the "meaningful" relationship to the observer (Flach, 1989). Overall, the core idea of EID is to make the abstract properties of the controlled processes, the relationship in the deep structures, visible to the operators - "make visible the invisible" (Rasmussen & Vicente, 1989). What shapes EID with the other traditional ID approaches is that it aims to resolve the control issues in complex high-tech systems (Rasmussen & Vicente, 1990). While EID still considers the importance of information processing capabilities, it expands the scope of analysis to the work domain, forming a triadic HCI model to address the concerns of context and functional constraints of the work ecology (Flach, 2015; Flach, Bennett, Woods, & Jagacinski, 2015). The emergence of EID coached by AH and SRK has a vital meaning in the development of HCI research, as it suggests that good design for complex sociotechnical systems cannot be achieved without adequate knowledge and understanding of the work domain (Bennett, 2017; Bennett & Flach, 2011).

ID is not just about visualisation of user interfaces, but could become representational issue relative to functions in the system (Smith, 1989; Stary & Peschl, 1998; Woods, 1991). As discussed in the appended articles later on, the ecological perspectives have led to many implications about the importance of considering the relationship between human and work, which sets a theoretical foundation for formative work description and analysis applied in future maritime research (Rasmussen et al., 1994; Vicente, 1999).

2.3.2 Thinking Big: Human-Automation Interaction and Systems Perspective

Interface Design is an important issue because "it is where problems with human-automation interaction are revealed" (Pritchett & Feary, 2011, p. 278). These ecological ideas also motivate modern HCI studies to go beyond the interface mechanisms at the microscopic level and "think big" (Hollnagel, 2011) to examine the nature of human-automation interaction (Pritchett & Feary, 2011). But what does it really mean when we have automation and human users to interact with each other? This section will first present relevant literature that examines various issues in interaction with automation. It also reviews the relevant literature regarding the systems perspective. Reason (1990)'s "Swiss Cheese Model" is probably one of the most well-known models in terms of accident analysis and means of communication. The "defensive planes" or the series of "barriers" (i.e., decision makers, line management, preconditions, productive activities and defences), represented as slices of cheese, illustrated how accidents might occur when a trajectory of accident opportunity through the multiple defences is created. The notion of "active failure" triggered by "latent failure" and queries into organisational factors and management issues (Reason, 1990, 2000) shows a tendency to go beyond the cognitive psychology to "think big" - although Reason's approach may still be considered as a "linear view of accident trajectories" and incapable of "accounting for multiple causalities with different time span", it reflects a shift of interest away from the traditional perception of human error (Le Coze, 2013). The system is more than just humans and machines but a combination of social systems and technologies. The sociotechnical system model, which symbolises a means of systems perspective, has been mentioned more often to holistically examine how the system works and investigate means to ensure the system as a whole operates within the boundaries of safety (Grech, 2008; Koester, 2007; Rasmussen, 1997), for example to adopt a larger or more global perspective in design (Dekker, 2011; Hollnagel, 2011). This section will present the trend towards these global perspectives with the impact of ecological concerns – thinking big.

2.3.2.1 Interaction with Automation concerning Effectiveness and Efficiency

Human-Automation System considers that "human operators are intermittently programming and receiving information from a computer that interconnects through artificial sensors and effectors to the controlled process or task environment" (Sheridan, 2002, p. 115). Humans serve as supervisory controllers responsible for directing and overseeing the machine's performance (Endsley, 2016b). Over the past four decades, human supervision of automated systems has essentially been developing a formality of coupling and communication between humans and machines (Sheridan, 1992, 2002). There is considerable research literature concerning autonomy and its connection to system effectiveness, such as the strengths and weaknesses of humans and machines. Such discussions have led to the thought of function allocation, analysing and deciding whether a particular function should be accomplished by a human, or a machine for improved efficiency (Fitts, 1951; Jordan, 1963; Kantowitz & Sorkin, 1987; Sharit, 1997; Sujan & Pasquini, 1998). Parasuraman, Sheridan, and Wickens (2000) contended that automation can be applied to four types of functions: (1) Information acquisition; (2) Information analysis; (3) Decision and action selection; (4) Action implementation. By following the general idea of distributing tasks in a human-automation system, some taxonomies were proposed to describe the level of automation (LOA) or degree of automation (DOA) and the automation functions (Endsley & Kaber, 1999; Kaber, 2017; Parasuraman et al., 2000; Riley, 1989; Wickens, 2017). Kaber (2017) argued that LOA provides a useful perspective to guide design. John (2017) believed that this provides a common language to address some human performance concerns that might otherwise be neglected, e.g., it is critical to intervene with manual control when needed.

While automation has great advantages for quality control and performance efficiency in handling routine tasks, it might provide the least help for the human operators to solve problem when there are unexpected events. This is known as "ironies of automation" (Bainbridge, 1983). Woods (1996) also described automated systems as "strong, silent, clumsy, and difficult to direct". Many human factors related issues were observed and framed in various terms (see Table 2). Inadequate observability and poor feedback from automation interfaces have been frequently referred as outstanding issues in HMI (Billings, 1991; Lundh, MacKinnon, & Man, 2015; Lützhöft & Dekker, 2002; Norman, 1990). Although many cited works focus on the psychological processes impacted by the introduction of automations, some of them appreciated the systems perspective to understand the automation issues. Other studies found that system factors, including system validity, reliability, robustness, system understandability, timeliness and integrity, can influence trust more than individual or situational factors (Endsley, 2016b).

Since World War I, machines have become more autonomous and have assumed many of the roles of their human operators. However, today's high degree of automation may still be incapable of handling unanticipated abnormal situations, which leaves the operator to remain the last barrier as a critical decision maker and problem solver within the system (Boy, 2011). The limitations of the LOA or DOA approach thus become more obvious: the value can be considered limited in just identifying how humans interact with "isolated elements of automation" instead of addressing issues in the network of humans and machines (John, 2017). Particularly, the DOA or LOA concept has been criticised for encouraging reductive thinking (Bradshaw, Hoffman, Woods, & Johnson, 2013) and providing little help to address the needs to make humans and machines work together to accomplish complex tasks (Lützhöft & Dekker, 2002). Automated systems are becoming more capable and truly autonomous but unexpected events and automation failures may hardly be ineradicable, representing huge complexities in the actual field (Woods, 2016). The traditional role of a human operator is shifting (Hoc, 2000) – there is a growing need for the human-automation system to work in teams with common goals (Klein, Woods, Bradshaw, Hoffman, & Feltovich, 2004; Lützhöft & Dekker, 2002). In a human-automation system, what is mostly required for improving effectiveness is not necessarily enhancing each agent's capability, but their integration in collaborations (Behymer & Flach, 2016; Lützhöft & Dekker, 2002).

Table 2. Studies that describe automation issues.

Study	Context	Negative Outcomes	Primary Analytical Approach
(Norman, 1990)	Aviation	"Physical isolation" (isolated from the physical structure of the airplane and ship) and "mental isolation" (isolated from the system state)	Psychological perspective
(Endsley, 2011, 2016b)	Aviation	Low situation awareness, errant mental models and out-of-the-loop syndrome	Psychological perspective
(Parasuraman & Manzey, 2010; Parasuraman & Riley, 1997)	Aviation and Maritime	Automation bias and complacency (refers to the operator's purported behaviour of not conducting necessary system check but assuming "all was well" when the dangerous situation actually evolves); mis-use or disuse of automation	Focusing on the cognitive processes involved (psychological perspective)
(Chavaillaz, Wastell, & Sauer, 2016) (Sauer, Chavaillaz, & Wastell, 2015)	Aviation	Trust towards automation, automation complacency	Psychological perspective
(Mosier, Skitka, Dunbar, & McDonnell, 2001; Mosier, Skitka, Heers, & Burdick, 1998; Skitka, Mosier, & Burdick, 1999, 2000)	Aviation	"Error of omission" (the operator failed to respond or delayed responding to the systems irregularities), "error of commission" (the operator trusted the prominent parameters on one display despite contradictory information on other) of automation bias	Focusing on the psychological impact of automation on human operators (psychological perspective)
(Lee & See, 2004)	General	Over- and under-reliance or trust on automation	Analysed from organisational, sociological, interpersonal, psychological, and neurological perspectives
(Bradshaw et al., 2013)	General	Over- and under-reliance or trust on automation (over trust is a result of high self-directness and low self-sufficiency while under trust is a result of high self-sufficiency and low self-directness)	Analysed from the system's perspective (the system is modelled with "self-sufficiency" and "self-directness", freedom from outside control)

2.3.2.2 Systems Perspective concerning Safety

The quotation from Aristotle, “the whole is greater than the sum of the parts”, is widely known in systems theory. Systems theory advocates some properties have to be treated adequately in their entirety and it is important to understand systems as a whole in contrast with the analytical reductionism (Bertalanffy, 1968). The key to understanding an organisation lies in the interaction among the system’s components (Ackoff, 1971), where emergent properties arise. Safety is such an important emergent property that it only makes sense when the interaction relationship and context is considered (Leveson, 2017).

In fact, safety has always been one highlighted theme in systems theory related literature and safety research (Flach, Carroll, Dainoff, & Hamilton, 2015; Hetherington et al., 2006; Lestari, Jaswar, & Kader, 2014; Leveson, 2011). Though the rapid technology advances in the industry provide opportunities to enhance productivity, efficiency and safety, the end-users performance does not necessarily meet the expectations (Landauer, 1995; Rigaud et al., 2012). Many examples have shown that, in complex sociotechnical systems characterised by high-risk operations, rules, procedures and standards to specify safe ways of performing are as important as the design of tools. However, these regulations could be incomplete or ambiguous, sometimes forcing the practitioners to deviate from the expected “route” in order to meet the actual work constraints (Rankin, Lundberg, Woltjer, Rollenhagen, & Hollnagel, 2014). It has been observed that in many accidents where safety was obviously compromised and “human error” has been considered as one dominating factor (MAIB, 2000; Rothblum, 2000; Ventikos, Lykos, & Padouva, 2014). “Human error” is usually understood as an individual or a team’s behaviours exceeding certain limits of a system’s threshold or deviating from the expected norms, suggesting the importance of individual or team cognitive factors in safety investigations, such as situation awareness (Hetherington et al., 2006; Samantha et al., 2011). Such a view could be criticised as being exclusively focused on human fallibility (Reason, 1990) or individual limitations, making it incapable of understand safety issues in holistic terms (Dekker, 2004; Dekker & Hollnagel, 2004). Here several models are reviewed to inform the systems perspectives pertinent to safety considerations in a human-operated, software-intensive, complex sociotechnical system.

Rasmussen (1997) provided a safety control hierarchical structure in terms of risk management: the propagation of an accidental course of events is shaped by the activity of people situated at different levels in the model, i.e., Government, Regulators, Company, Management, Staff, and Work. Hierarchies are characterised by the control processes operating at the interfaces between levels, so the upper levels impose constraints on the lower ones through defined control actions (Leveson, 2017). The model describes how safety could be influenced by behaviours conducted at each level, e.g., “society seeks to control safety through the legal system” (Rasmussen, 1997, p. 184). The model is considered to represent the sociotechnical system as a “flow of information” between each level (Le Coze, 2013). Considering each level involves a range of research disciplines, from political science, social science to psychology, engineering disciplines, an interdisciplinary approach is required to understand the entire operation of the system and fathom the industrial safety problems (Le Coze, 2013). Rasmussen’s model becomes a foundation for many other derivative models, such as the safety control structure from Leveson (2017) to guide systems engineering practice.

In safety-critical industries, operations must be safe, profitable and meet the workload demands of the operators. The “Brownian motion” model of the boundaries of acceptable performance was developed to illustrate how the organisational behaviours could migrate toward accident under the influence of pressure toward cost-effectiveness in an aggressive, competing environment (Rasmussen, 1997). The boundary is not absolute as the system is framed as an adaptive system. Based on this ecological approach, variability is manifested in the process during which individuals express their own degree of freedom to adapt to the local constraints (Rasmussen, 1997). Safety depends on the ability of the system to remain within the boundaries (Le Coze, 2013). Dekker (2011) further synthesised this concept of "drift into failure". The drift is not because of operators' evil desires, inadequate vigilance or knowledge, instead, the deviation becomes a part of norm in high-risk operations. Risks could accumulate during the "incubation period", a period in which the incremental changes that may later contribute to a system-wide collapse get unnoticed (Dekker & Pruchnicki, 2014; Turner, 1978). It shows the importance to build adaptive systems to allow the operators to respond flexibly in an increased margin of manoeuvrability (Rankin et al., 2014).

Hollnagel, Woods, and Leveson (2006) proposed resilience engineering as a system approach that is consistent with Dekker's views. The early definition of resilience is the intrinsic ability of an organisation (system) to maintain or regain a dynamically stable state, which allows it to continue operations after a major mishap and/or in the presence of a continuous stress (Hollnagel et al., 2006). Later the definition of resilience was adjusted to the system's ability to perform in a resilient manner that it can adjust its functioning prior to, during, or following changes and disturbances to sustain required operations under both expected and unexpected conditions (Hollnagel, Pariès, Woods, & Wreathall, 2010). Another definition could be the system's ability to absorb disturbances and reorganise while undergoing change so as to still retain essentially the same function (Walker, Holling, Carpenter, & Kinzig, 2004). Resilience could also be deemed as a general ability to have adaptable reserves and flexibility to accommodate the unforeseen contingencies (Mikkers, 2010; Nemeth, 2008). In Hollnagel's concept, resilience is about having adaptability and flexibility in the system rather than avoiding failures. An operational practice of resilience engineering requires that all levels of the organisation are able to learn from past events, understand what happened and why, monitor short-term developments and threats and adapt risk models, respond to actual events in an effective, flexible manner, and anticipate long-term threats and opportunities (Hollnagel et al., 2010). Resilience engineering adopts the philosophy of holism opposed to reductionism and acknowledges the importance of ecological perspectives, because the ecological approaches concern with how the system (human-interface-ecology) functions as a whole. Resilience engineering also inherits the notion of variability, which is introduced by Rasmussen's research work (instead of understanding the system through the lens of human error) (Le Coze, 2013).

Chapter 3: Methodological Framework

This chapter presents the methodological tools which were utilised in the various studies in the maritime domain. Elements of this chapter outline the author's academic development in Doctoral research programme, with references to research publications. More details about the experiment procedures, apparatus used, confidentiality and other ethical considerations could be found in each individual paper.

The purpose of the research programme, as stated in Chapter 1, is to generate theoretical and usable knowledge about human-technology interaction in complex maritime sociotechnical systems through learning and understanding human factors related issues. Although the author took a practical but exploratory path across multiple applied projects (explained in section 1.1), the aim is never just to achieve specific project goals but to use these projects as means to explore different perspectives of HCI/HMI to form an improved understanding of "human error", "automation issues" and problems with fast digitalisation in the shipping domain. The projects were mainly investigated through the multidisciplinary lens of psychology, sociology and ecology and the theoretical constructs relative to each lens have been discussed in the appended articles. The exploration in multiple dimensions not only aims to contribute to the greater scientific body of knowledge but also hopefully enlighten future HCI research towards an interdisciplinary approach.

However, it should also be noted that how the author was involved and participated in the projects might have influenced the methodology. People that set up and develop these technology-driven projects usually come from a highly technological context with a technology-centric mindset. The role for the author was to support project development with coordinated research practices within the project settings. Although the thesis author was the main contributor to planning, execution of data collection, analysis and writing of the appended articles for which this thesis is based on, he did not necessarily have direct control of the system design, or had practical constraints in methodological considerations in many circumstances, due to the project settings and configurations. Nevertheless, the research has indeed involved a variety of methodologies that have formulated the basis to understand human-technology relationship and thus, the knowledge was accumulated in a non-linear way.

3.1 Methodological Tools

The methodological tools selected cover data collection and analysis to explore the human experiences and address the human factors related issues in human-technology interaction. The methods deployed are also widely used across human factors applications and research. Beside the quantitative data collection and analysis methods used in a quasi-experiment simulator study, the qualitative ethnomethodological approaches were mainly conducted in the projects to gain deeper understanding of the phenomenon under study.

3.1.1 Interviews

Interview is one of the most common tools in qualitative research to find out things that cannot be directly observed, in order to allow researchers to enter into the other person's perspective (Patton, 2002). It can be carried out in the forms of informal conversational interview, standardised open-ended interview and general interview guide approach (Patton, 2002). The interview guide approach lists the questions or issues that are to be explored in the course of an interview.

3.1.2 Focus Groups

A focus group is a type of collective interview with a small selected group of people on a specific topic, typically six to ten people (Patton, 2002). It is important in research for it keeps the interactions focused while allowing individual perspectives and experience to emerge (Patton, 2002). A focus group can create a communication space, i.e., an in-depth group interview, to help the researchers to "understand and explain the meanings, beliefs and cultures that influence the feelings, attitudes and behaviours of individuals" (Rabiee, 2004). Focus groups offer a flexible means to approach various features associated with a system (Stanton, Salmon, et al., 2006). The heterogeneity of participants is usually to be avoided as this might make the participants less comfortable in sharing experiences and thus lead to less interaction between the ones pertaining to different professions (Goodman, Kuniavsky, & Moed, 2012). Focus groups are suitable for identifying problems, finding desires and values from the stakeholders' view (Ivey, 2011) as it can provide insights into the sources of complex behaviours and motivations (Morgan & Krueger, 1993). In addition, focus groups can also be used to evaluate design with regard to error occurrence, usability, mental workload and situation awareness (Stanton, Salmon, et al., 2006). However, the participants may get influenced by other opinions in the ways of being more prone to group-thinking and reach group consensus (Goodman et al., 2012). The overall quality of the information obtained is largely dependent on the interviewer (Patton, 2002).

3.1.3 Questionnaires

Questionnaires, as a flexible data collection tool, can be utilised not only in the design processes to evaluate the conceptual or prototypical design, but also in the evaluation phase to elicit data regarding usability, user satisfaction, user opinions and attitudes (Stanton, Salmon, et al., 2006). There is already a plethora of standardised questionnaires that have been designed, developed and widely used for assessing human or system performance in a wide range of human factors applications, e.g., the Quality In Use Scoring Scale (QIUSS) for assessing usability (Sherwood-Jones, 2008), the Situation Awareness Rating Technique (SART) for assessing situation awareness (Taylor, 1990), etc. Noteworthy is that specific questionnaires can be designed and customized depending on the goals of the study (Stanton, Salmon, et al., 2006).

QIUSS is referred as the capability of a product system to enable specified users to achieve specified goals with effectiveness, productivity, safety and satisfaction in specified contexts of use (ISO/IEC, 2004). QIUSS was developed to give a simple broad measure of QIU - a lower score is assigned as a poor attribute to the dimension and a higher score reflects a positive rating (Sherwood-Jones, 2008).

SART is a post-trial subjective rating technique that was originally developed for the quantification and validation of pilot SA assessment (Taylor, 1990). Ten dimensions of the human-system integration were inquired for the measurement of operator's SA in order to evaluate the prototype of shore-based decision support system: familiarity of the situation awareness, focusing of attention, information quantity, instability of the situation, concentration of attention, complexity of the situation, variability of the situation, arousal, information quality and space capacity (Taylor, 1990). It requires participants to subjectively rate each dimension on a Likert scale of 1 to 7 based on their performance of the task under analysis (Stanton, Salmon, et al., 2006). Although the method was criticized for the correlation between performance and reported SA and participants do not necessarily know they have low SA, it is non-intrusive to primary task performance and has high in ecological validity (Endsley, 1995a; Stanton, Salmon, et al., 2006). In Article VI, a questionnaire was developed based on the dimensional contents from SART, but more specifically, it was tailored for the scenarios of remote supervisory control for unmanned vessels and shore control centres.

3.1.4 Observation and Thinking Aloud

Observation is an important data collection process frequently used in the field regarding the physical and verbal aspects of a task (Stanton, Salmon, et al., 2006). The most widely used form is direct observation and a researcher records visual and audio information about an ongoing task (Stanton, Salmon, et al., 2006). Many other terms have also been used to refer to field-based observation, such as participant observation, fieldwork, qualitative observation and field research (Patton, 2002). Noteworthy is that although these are largely used for field studies, which involves going to the actual workplace and observing events as they occur in the real world and real-time settings (Hendrick & Kleiner, 2001), observation is also commonly used in laboratory studies (Jackson, 2017; Jersild & Meigs, 1939; Woehr & Lance, 1991).

The observation process usually accompanies informal conversational interviews (pre- and post-observations), field notes taking and having the participants think aloud. Informal conversational interviews indicate the spontaneous generation of questions in the natural flow of an interaction between the observer and the ones who are under observation (Patton, 2002). Field notes are the written materials developed by the observers as their own method of describing what has been observed/experienced and even the observer's feelings, insights and interpretations. They serve as a fundamental basis for discovering variables in qualitative research (Patton, 2002). Having participants think aloud is a frequently used research method in which participants speak aloud their thinking as they are performing tasks or solve problems (Charters, 2003). This is also known as concurrent verbal protocol in which the participants' verbal descriptions of the tasks and decisions are made explicit without leading to changes in their task performance (Bainbridge, 1979; Bowers & Snyder, 1990; Gagne & Smith Jr, 1962; Smead, Wilcox, & Wilkes, 1981; Wright, 1992). It offers the observers personal insights of the participants and uncovers the unique source of key information used in problem solving (Someren, Barnard, & Sandberg, 1994), such as explanations of what the participants do and why they prefer to do it in such ways and allows tacit knowledge to be quantified. Thus to some extent the participants are considered as "quasi-researchers" (Charters, 2003).

However, not all tasks or subjects are appropriate for using thinking aloud, because it is essentially a method for acquiring data about a cognitive process and there could be problems with synchronization (e.g. people slow down the reasoning process to synchronise it with verbalisation) and working memory (e.g. when the information is non-verbal and complicated) (Someren et al., 1994). In the appended articles, both participants and performed scenario-based tasks were carefully selected as recommended by Someren et al. (1994), in order to minimize the negative effect of possible distruptive effects of thinking aloud. For instances, the participants were Subject Matter Experts (SMEs) with considerable operational experience while the levels of difficulty were pre-assessed by other SMEs so that the tasks were neither too difficult nor too easy.

3.1.5 Grounded Theory

The data collected from observations, individual interviews, focus groups, audio-visual materials and documentations, compose a series of field notes and transcripts that form a synthesis to describe a specific world reality within a specific time span. Grounded Theory, a qualitative data analysis method, commonly serves as an appropriate tool for qualitative inquiry. It strives to categorize themes in the descriptive materials and generate explanatory propositions or schemes that correspond to real-world phenomena (Corbin & Strauss, 2008; Patton, 2002). Grounded Theory allows theoretical concepts or frameworks to emerge from the data throughout the research process, as an analyst must "feel his/herself through" (Corbin & Strauss, 2008). However, it shall be noted that "people can do quality research without going on to the final step of theory building" (Corbin & Strauss, 2008, p. x) and it could be used for "thick and rich description" (p. xi) or conceptual analysis in knowledge elicitation (Pidgeon, Turner, & Blockley, 1991).

Grounded Theory usually starts with organizing information to basic description (using "memos" to inform coding), then moves to conceptual ordering by forming categories, and last comes to theorizing to formulate the explanatory propositions (Corbin & Strauss, 2008; Patton, 2002). A set of detailed line-by-line coding procedures, i.e., open coding (identify concepts, properties and dimensions of the data) and axial coding (coding occurs by linking and relating concepts) are utilised as a basis to emerge initial categories and suggest relationships among categories, which become a foundation for higher-level categorization and theorizing (Corbin & Strauss, 2008; Patton, 2002). Comparative analysis is central during such a process as it allows analysts to discern how patterns are emerged and dynamically evolved (Patton, 2002).

Subjectivity may become a potential threat to the quality of the Grounded Theory based research but complete objectivity is impossible (Corbin & Strauss, 2008; Patton, 2002). However, subjectivity, such as the prior knowledge of the analyst that can enhance sensitivity, could also become useful to inform analysis rather than directing analysis (Dey, 1999). Standing in contrast to objectivity, sensitivity shows the ability to pick up subtle nuances and cues in the data (Corbin & Strauss, 2008). It can drive the interplays between the analyst and transcripts in which understanding of what it really means in the data gradually evolved until the "aha" moments arrive (Corbin & Strauss, 2008).

In cases where Grounded Theory was used in the appended papers, the transcripts were imported, coded and analysed in MAXQDA software developed by VERBI Software GmbH (Kuckartz, 2014). The software supports the research practice rather than direct it, by providing the possibility to retrace the analytic process whenever it is necessary, as the researchers can navigate themselves through the different coding opportunities. The ability to provide the "audit trail" improves the research's "reliability" (Corbin & Strauss, 2008), which is also enhanced with the participation of SMEs in analytic research activities.

3.1.6 Prototyping

In the MUNIN and GOTRIS projects the software systems were developed as prototypes for evaluation purpose. Though the author only participated partially in the prototyping work in the MUNIN project, prototyping was recogonised as an important research method in the design phase. There are many forms of prototyping and fairly high fidelity protoytpes were developed in these projects. For example, in the MUNIN project, the computerised supervisory system was prototyped and deployed in a way that could be integrated with different ship simulators to provide real-time data of different simulated unmanned ships.

In fact, the prototypes were essentially representations of design ideas regardless of the medium (Houde & Hill, 1997) or considered as manifestations of conceptual ideas (Lim, Stolterman, & Tenenberg, 2008). The critical role of prototyping is more than just "being a vehicle" for design. The concrete manifestation can "unlock cognitive association mechanisms related to visualisation, prior experience, and interpersonal communication" so that prototyping has a strong connection to the knowledge-building in the process of concretisation and externalisation of thoughts (Berglund

& Leifer, 2013). In addition, prototyping provides an important basis to detect problems and significant deficiencies in design (Endsley, 2011), which is not only useful for improving current systems in use but also provides insight into the shaping of future systems.

3.3 Procedure

This section summarises the basic procedures considered for each appended article within the thesis. More details can be found in the appended articles. For Article I, II and IV which are scenario-based studies in a ship simulator environment, achieving statistical significance is a challenge due to practical data collection contraints, such as facility and professional mariner volunteers availability during scheduled project milestone events. Table 3 provides a summary of essential information of these studies.

Table 3. Overview of the procedures in the appended articles.

Article	Project	Research Context	Number of Participants	Duration per Participants (including familiarisation)	Experimental Design	Number of Scenarios /Sessions
I	MUNIN	simulation	5	6 hours	within-subjects	5 scenarios
VI	MUNIN	simulation	6	5 hours	within-subjects	4 scenarios
II	GOTRIS	simulation	8	4 hours	within-subjects	1 scenario
III	EE Optimisation	workshop	13	1-1.5 hours	focus group interview	2 sessions
IV	EE Optimisation	conceptual article	N/A	N/A	case study	N/A
V	EfficienSea 2	conceptual article	N/A	N/A	literature review	N/A

3.3.1 Article I

In the MUNIN project, the onboard autonomous ship controller controls the unmanned vessel as per a pre-voyage plan. The remote simulated ships regularly send ship information to the Shore-based Control Centre (SCC) operator. Each operator is required to monitor six unmanned vessels' status by cycling through each of the six dashboards in a monitoring and controlling workstation. Five participants were invited to take part in the scenario-based trials and debriefing interviews. Five scenarios, developed by SMEs, were presented to the participants over a two-day period. These scenarios were used to assess the functionalities of the SCC prototype system and the performance of the participants while they undertook various SCC roles. All scenarios and post-scenario interviews were recorded by a video recorder for further analyses. The direct observation was used and field notes were documented. All participants in the scenario were encouraged to think aloud. After each scenario, the participants were asked standardised open-ended interview questions. Questions were developed for the exploration of the participant's sense making process, behaviours, opinions about the team performance, as well as identification of usability problems.

3.3.2 Article II

Eight experienced pilots volunteered to participate in an experiment that examined navigating simulated ships in the inland waterways of Gothenburg region and participated in follow-up debriefing interviews. Each scenario lasted about 3 hours. In each run of the scenario, there was one pilot, one student, one observer, one IT professional, and one simulation assistant standby (acting as the bridge administrator). The pilot would navigate the ship with the student's assistance from Marieholmsbron (Marieholms Bridge) to the Götaälvbron (Göta River Bridge), but it was up to her/him when and how to use the tablet-based GOTRIS programme for making schedules of bridge passing. They were encouraged to think aloud their thoughts and intentions. Direct observation method was utilised by the experimenter to collect data regarding the physical and verbal aspects of the scenario, including individual actions, errors made, communications between individuals, the technology involved in the scenario and the system environment. After the simulation run, the pilot was asked to fill in the QIUSS questionnaire. Then they would be interviewed with the usability questions followed by an open-ended discussion on the GOTRIS application.

3.3.3 Article III

In total, five male ship engineers and eight male bridge officers were invited to participate in two focus groups that were conducted chronologically in this study. The focus group study was done in a workshop, which was pre-planned together with Sweship Energy (a platform created by the Swedish Maritime Association and supported by the Swedish Energy Authority and Swedish Maritime Administration) to facilitate knowledge sharing and collaborative learning. Three engineers and four master mariners were invited to participate in the first focus group study while the other two engineers and four master mariners in the second one. Each focus group discussion had two parts. The first part was a brief discussion on a few general questions pertaining to EE operations onboard. The second part was an in-depth discussion, looking more into the details of their perceived value, challenges and expectations towards the design and usage of an ideal digitalised EE monitoring tool.

3.3.4 Article IV

This article uses the practices of EE onboard ships as a case to discuss how knowledge mobilisation should address this context change and uncovers how existing knowledge networks in the shipping industry would evolve in this emerging data-driven ecology.

3.3.5 Article V

This conceptual paper presents a literature review and a design case in an Engine Control Room (ECR) on a merchant ship. The literature review focuses on the problems in the ECR and relevant theoretical constructs. An applied solution is also brought up for discussion.

3.3.6 Article VI

Six male participants were invited to take part in the scenario-based trials and debriefing interviews. The scenario-based tests were performed at the operator's monitoring and controlling workstation in a mocked-up SCC. The SCC's concept is almost identical to the introduced one in Article I. Ship simulators were employed to provide real-time data of different simulated ships and an operator was responsible to monitor six semi-autonomous unmanned vessels. However the user interfaces are assembled in different ways. The operator needs to be prepared for any contingencies and might take remote control of the unmanned ship for collision avoidance purposes. All four scenarios were developed by SMEs. The primary tasks in all scenarios are collision avoidance (CA) activities based on locating and identifying other traffic using radar and Automatic Identification System (AIS) information. In addition, a few secondary tasks were added to the scenarios. The operator was required to quickly diagnose if this was a false alarm and provide engineering maintenance or navigation suggestions if applied. The Wizard of Oz technique (Kelley, 1984) was utilised to trigger the alarms in primary tasks by lighting up the corresponding panel at a pre-planned time point. All six participants would go through scenarios 1 to 4 (in total 4 runs per person) over a three-day period, in a randomized order. It took approximately 20-30 minutes per scenario and 30 minutes for the debriefing after each run of the scenarios. During the scenario, the participant was encouraged to keep his navigator hat on when examining the familiar instruments while verbalizing his thoughts aloud. There was a research assistant standing by whose duty was to keep track of the participant's behaviours. A video camera was used to record each trial and was used in subsequent analyses. A questionnaire was developed based on SART, but more specifically, for the scenarios of remote supervisory control for unmanned vessels and shore control centres.

Chapter 4: Results

This chapter highlights the findings from different projects to provide a basis for the discussion. More detailed results can be found in the appended articles.

4.1 Article I

This article first reveals how SA requirements had been influenced when relocated navigators from ship bridges to the SCC in the MUNIN project settings. The theoretical analysis suggests that analyses on technology, environmental conditions, operational requirements and user's characteristics are required to address the SA requirement changes. Based on the direct observation, scenario recordings and post-trial interviews, the study identifies several significant human factors related issues regarding human performance and organisational structure described by participants: degraded performance in detection of abnormity and generation of the alarm, loss of ship sense (the gut feeling regarding the manoeuvring of the ship (Prison, Lützhöft, & Porathe, 2009)), passive monitoring and out-of-the-loop syndrome, ill-adapted mental models to the new situations and unclarified organisational hierarchy and regulations. These issues not only undermine the operators' capabilities to understand how critical the situation was at sea and how it would evolve in the future, but also degrading the overall team (SCC) performance in critical situations. The study results revealed that the system prototype had severe issues that hindered the development of both individual SA and team SA. Interface design must consider the SA requirements changes in the context of use.

4.2 Article II

The article revealed that the participants were slightly positive about this tablet-based application, but the ways of using the service and the trust about the application varied depending on the navigation situation. The application was most frequently used when the location of the ship was far away from the bridge. Once the ship was getting closer to the bridge, the pilots would change their reliance from GOTRIS to their own judgment as well as other conventional electronic nautical charts and VHF radio calls. Almost all pilots diverted their attention from these mobile devices when they were performing safety-critical bridge passing manoeuvres. The data reception delay was identified as a serious problem affecting user experience significantly. The application was ignored most of the time. Additionally, the pilots reported that they sometimes found it difficult to understand the meeting view within the tablet or made much effort searching and filtering out the right data.

All participants thought the tablet application was not absolutely needed in their everyday work practices. Some believed it was meaningful to have the Estimated Time of Arrival (ETA) and recommended speeds in the system for the purpose of building equally trustable parties, such as the railway and river traffic. Others believed that the tablet could well be integrated in the electronic navigational charts in some ways for better usability.

4.3 Article III

The main message delivered from the discussion with study participants was that distributed working communities (the bridge and engine department) believed it was important to collaborate and inspire each other. Collaboration was considered as a useful approach to increase personal awareness on EE. The tools played a crucial role in their work. As more automation is introduced to their workplaces, information overloading and reduced transparency were recognised as a problem.

In the in-depth discussion, the participants addressed the key activities that contribute to EE, the values of mediating technologies in terms of how they can contribute to mutual understanding and the common ground, as well as the potential barriers to achieve improved EE performance in three phases of a voyage. The emerging theme is to support the need of information sharing, communicating and collaborative learning via mediating technology on EE optimisation. In the pre-departure phase, the participants expected that the voyage planning tasks should involve both departments and be supported with the provision of an overview of the systems and route options. During the voyage, the participants expected an open contact between the two departments and the tool could support relevant situational information sharing like current, wind and traffic. In the post-voyage phrase, performance evaluation and collaborative learning experiences with the engagement of the tool was highlighted by all the participants yet it does not exist today. Some challenges were also addressed by the participants, such as time constraints, system complexity, and usability of the tools.

4.4 Article IV

Rapid development in artificial intelligence and big data analytic applications have had a significant impact on knowledge mobilisation across industries including the shipping domain. This paper used the practice of energy efficiency onboard ships as a case study to discuss how knowledge mobilisation should address this context change and uncovers how existing knowledge networks in the shipping industry would evolve in this emerging data-driven ecology. The transition in knowledge management under these sociotechnical impacts will likely evolve from existing predominant *hobby networks* and *professional learning networks* towards *business opportunity networks* and *best practice networks*, where the benefits of such knowledge mobilisation and creation will benefit the organisation, provided the necessary managerial support is provided. The system development in the shipping domain would be more tightly-coupled and complex with various human-machine configurations. From a systems perspective, the study discussed the characteristics associated with knowledge mobilisation processes in the new technology landscape and exemplifies how the prerequisite capacities important for knowledge translation could be represented at multiple levels, i.e., the departmental, organisational, industrial and social levels.

4.5 Article V

The work practices in the ECR are becoming increasingly demanding and complex with growing presence of IT applications. This paper has proposed shifting the focus from patching individual problems by continuously introducing more and more intelligent artefacts to the holistic systems thinking. An architectural approach is discussed to suggest that a certain degree of standardisation should be considered as a prerequisite to allow technologies to be better integrated and governed in the back-end, which can influence user experience and safety performance in the front end. The ECR design case revealed that the trickle-down regulations in the maritime domain must consider the configurations between the human workers and the emerging technologies to the address the increasing complexity onboard. This paper also concludes that without holistic systems thinking on a global scale, whatever tech-innovations that are introduced to workplaces onboard today will likely become unruly technologies, which may eventually erode the adaptive capacity of the man-machine system and compromise safety and efficiency.

4.6 Article VI

In this paper, a remote supervisory control prototype was developed on top of a fully-fledged ship bridge system to support monitoring and controlling of remote simulated unmanned cargo vessels. The results suggest human factors related issues could remain in systems assembled by assumed reliable technological components. Perfect technological pieces do not compose a perfect system, as the contextual factors were downplayed in the design and fast prototyping development process. Prominent challenges include psychophysical and perceptual limitation for the operators, decision making latencies and automation bias which is applicable to usability issues of interfaces, deprivation of ship sense and lack of current regulatory oversight. The interfaces were supposedly mediating tools to inform the operators of the events in the remote field, but without adapting the tools to the domain constraints, they were limited in remote supervisory control tasks oriented to autonomous unmanned ships. The findings from article VI suggest that interface design needs to account for the contextual factors from an ecological perspective. The underlying user-environment coupling, an important ecological concept, must not be ignored when moving people from ship to shore. The system transparency would largely depend on how the interfaces can account for the radical change of the work domain constraints in the SCC, which forms an enlightening ecological lesson for future system design.

Chapter 5: Discussion

This chapter extends the results presented in the previous chapter and discusses the implications of the findings by relating it to other scientific work published regarding the topic of human-technology interaction. The chapter begins with a psychological discussion about human limitations in supervisory control and the conventional technology-centric or "cognitivist" ways of designing, developing and deploying technologies in the shipping domain. This is followed by a discussion with socio-cultural perspectives to address the sociological concerns. The psychological and sociological concern both inform concerns in an ecological dimension, where human errors, wicked problems in automation, issues in interface design in the shipping context were reflected upon. The systems perspective is also discussed, together with its implications for the future development in the maritime domain. In addition, the connections between each dimension derived from various studies were woven into the discussions above, serving as a base to unfold a philosophical meditation and a query into epistemology. This hopes to shed light on the emerging language of sociotechnical systems and provide an outlook on future recommendations for research directions. This chapter concludes with a methodological discussion, which justifies the way in which the included studies were conducted. It also provides reflections about its limitations and constraints.

5.1 Human Performance

5.1.1 Human Limitations

As mentioned in Chapter 1, the shipping industry is currently undergoing a major transition towards full autonomy and high degree of digitalisation, which is characterised by fast introduced digital artefacts and services, with a dragging tail of slow regulatory development. The international projects MUNIN (Article I and VI) and GOTRIS (Article II) provided an appropriate context to explore how advanced technologies aiming at high degree of automation and digitalisation could impact shipping, particularly the human performance at the sharp-end.

The MUNIN project's settings are that every SCC operator is required to use six dashboards to remotely monitor six autonomous unmanned vessels. A data communication channel connects the SCC control system and controlled process in the autonomous unmanned vessels, forming an essentially remote supervisory control system (Sheridan, 2002) (see Figure 6). Thus the operations to maintain the safety of the controlled vessels, such as reading the warning signals on the screens and acting accordingly, are considered as "remote manipulation" (Rasmussen, 1986).

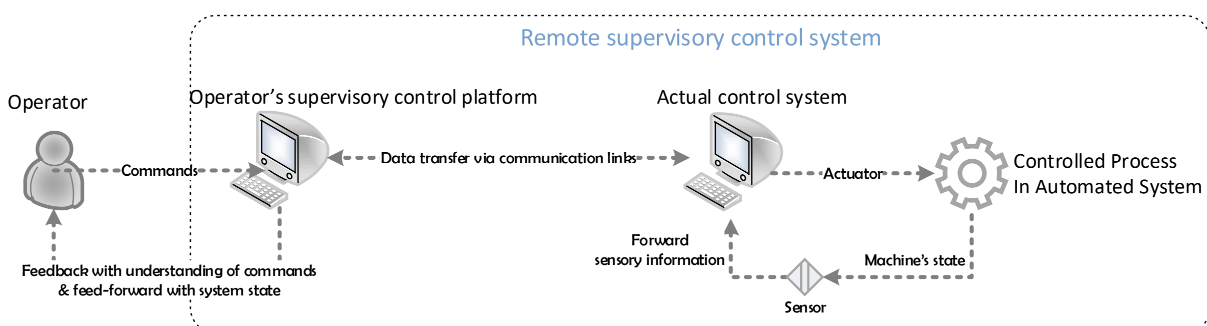

Figure 6. A remote supervisory control system.

The work of remote manipulation at the SCC is essentially multi-tasking: the operator needs to deal with the coming alarm on the vessel, finding out probable causes with some preliminary diagnostic moves while staying “vigilant” towards any new critical alarms from other vessels. It requires the operator to scan the displays frequently and switch between different information sources. One observed problem in Article I and VI is that the participant might fail to attend to new alarms if he/she got “trapped” in dealing with an existing alarm. This is exactly what Endsley described as *attentional tunnelling* that the operators “lock in on certain aspects or features of the environment…will either intentionally or inadvertently drop their scanning behaviour” (Endsley, 2011, p. 32), which is the most common situation leading to an SA failure (Endsley, 2015). Although adjacent phenomenon such as workload and information overload can influence attention (Fiske & Neuberg, 1990; Speier, Valacich, & Vessey, 1999; Szalma et al., 2004), to explore the possible underlying causal factors, we need to go deeper about attention’s role in information processing (Wickens, 1992) and understand how different mechanisms fundamentally influence the allocation of the selective attention (Koch, 2004; Parkhurst, Law, & Niebur, 2002). During the diagnostic process, the operator’s goal-directed attention is in the top-down form, depending on the task goals. The problem is that there seems to be an information processing bottleneck that prevents part of the sensory information to reach visual awareness. Pre-attentive computation of visual/audio features can be significantly modulated and influenced by the overall context in which the stimulus is presented and the mind-set in which task goals are shaped (Itti & Koch, 2001). Itti and Koch (2001)’s research informed that whether or not be able to attend to new stimulus is most likely a result of coordination and competition of involved bottom-up and top-down selective attention processes (introduced in Chapter 2).

Mental models play a crucial role in coordination and competition (e.g., how it can influence volitional deployment of attention): As a representation of the world and their meanings and knowledge (Johnson-Laird, 1983), it provides a critical mechanism to interpret the significance of information and make sense of the world. With the novel situations (including unfamiliar task conditions and vagueness of the regulations), the operators’ behaviours were “knowledge-based” at a higher conceptual level (Rasmussen, 1987). Endsley (1995b) described the process in which the schema is activated, mental model gets updated to interpret the feedback and intentions are directed in a goal-oriented pattern. In the SCC, all participants were experienced master mariners, but they were never working as the SCC operators to monitor and control multiple vessels prior to the experimental scenario runs. The dominant mind-set is to maintain the safety of own vessel during navigational activities. With six vessels to be managed, the participants have reasons to be stressful under this unfamiliar situation, which is usually associated with selective attention (Rasmussen, 1986).

However, the results are not entirely explained by a lack of familiarity but also tightly related to how information is organised and presented to the SCC operator. The MUNIN studies also suggest that reduced information and transparency in the distributed context can create out-of-the-loop syndrome, introduce automation bias and undermine SA significantly, even highly reliable technical components are utilised. Automation may reduce the operator’s workload when it functions well, but it can cause problems if there is a malfunction (Bainbridge, 1983; Norman, 1990). The problem may not be about over automation, but feedback (Norman, 1990). The feedback the operator receives is only visual information in the SCC. Perhaps the failure to attend to a new alarm in the MUNIN experiments is also subject to the lack of audible warning embedded in the interface (e.g., how attention is influenced in the bottom-up mechanism). In addition, it is necessary to recognise how the interaction formality has been changed in the SCC. When a navigator conducts ship-handling on a ship bridge, the "gut feeling" is of paramount importance for the navigator to understand the ship status and subtle dynamics within the environment in a more efficient way compared to traditional the electronic displays (Prison, Dahlman, & Lundh, 2013). For instance, the kinetic movement and vibrations could imply the both the internal ship status (e.g., fully loaded cargo) and external environment effects on the manoeuvrability of the vessel. Performance onshore or onboard is related to effect of "presence" (Barfield & Hendrix, 1995; Lombard & Ditton, 1997): First it enables the subjects to verify information through multiple information sources (i.e., screens and environment), each of which is associated with different levels of reliability. Second, it can facilitate the subjects to actively pay attention to the dynamics to develop sufficient SA in a non-linear process. However, the results from article I and VI revealed that the operators can only rely on the information on the display - the SCC's interface design did not address these concerns sufficiently and thus in a way prevented the human operator from conducting early detection of the irregularities. The impact of the information from the environment on the operators is even observed in the GOTRIS project that "they kept looking out of the window and adjust manoeuvre" and in the end they stopped using the so-called decision support tool, because of the limited help it provides to achieve the task goal. What designers believe is useful (e.g., set up more screens in the SCC to be able to compensate information loss in MUNIN or establish digital service about speed recommendation to be able to optimise ETA of passing under bridges in GOTRIS), could be useless in the user's world as the context factors and work constraints were not sufficiently incorporated and addressed in the design.

5.1.2 Design Implications

All discussions around SA, mental strategies, allocation of attentional resources, "gut feelings", decision making processes, not only help us to approach the RQs about how advanced technologies in the shipping domain impact human performance, but also uncover the prominent human factors related challenges and gaps in the design and use of digitalisation or/and automation technologies. The common problems accompanying SA degradation, such as "vision tunnelling", "out-of-the-loop", "errant mental models", "automation bias" (Endsley, 2011) were identified as prominent automation issues that operators have been confronting in the studies examining human performance in supervisory control tasks. Human limitations are the central issues based on the findings from both the MUNIN and GOTRIS projects, pinpointing the answers to the RQs about how psychological information processing-based approaches perceive human-technology interaction. But how this can inform the design?

An important contribution of the research on attention regarding the interplays between visual characteristic and human information processing capabilities, is that it points out HMI displays need to support critical aspects of attention, which are *selecting*, *focusing*, *dividing* and *sustaining* in the workplace (Wickens, 1992; Wickens, Lee, Liu, & Gordon-Becker, 2003). The design of future decision support systems needs to explicitly consider this important aspect, i.e., "an attempt to match the information process of the computer to the metal decision processes of an operator" (Rasmussen, 1986, p. 2). This is to say that HMI design needs to concern itself with the cognitive attributes of the operator and communicate the results to the operator in a form that is compatible with the operator's perception-action cycle and decision making strategy (Endsley, 2011, 2015; Rasmussen, 1986). According to the "data/frame theory" (Klein et al., 2007) which is, to some extent, similar to Endsley's SA theory, a HMI's capability to support a user to make sense of the world is largely due to how efficiently and effectively it was assisting to build the "frame" to select the "data" and use the existing "data" to construct appropriate "frame" in a reciprocal manner. This is because, the operator's efficiency in coping with complex information can highly depend upon "the availability of a large of repertoire of different mental representations of the environment from which rules to control behaviour can be generated *ad hoc*" (Rasmussen, 1987, p. 258). More importantly, the design must consider that how the interfaces can accommodate for the contextual change, not only reduce the visual demands of displays, but also support the operator's adaptive performance in dynamic task allocation (Engström, Markkula, & Trent, 2009). The SA requirement analysis (as a part of the design process) in Article I shows the potentials of the SA-oriented design (Endsley, 2011), which may be appreciated for its values in coupling human capabilities/limitations and interface design to generate concrete design guidelines solutions. For example, a specific design instance could be making manoeuvrability of the vessel as salient cues at a proper time as the dynamic situation evolves to the improve the operators' SA, which could become a hypothesis for future laboratory studies.

5.1.3 Beyond Psychological Dimension

Parts of the core contributions of these studies are that they predominately departed from a psychological perspective, surprisingly landing on sociological and ecological perspectives. The findings from Article I clearly suggested that the current organisational hierarchy and regulations caused critical problems in the work at SCC. Based on the current chain of command in an unchanged organisational structure, the captain (a role that the project settings assume still exist in SCC) became the team-SA chain's weakest and most vulnerable link when he had difficulty developing SA about the situation. The organisational factors and the "COLREGs for unmanned ships" (i.e., International Regulations for Preventing Collisions at Sea as the "rules of the road" at sea) were relatively downplayed in the technology-centric project. It might induce errant mental models for these navigators in supervisory control tasks towards multiple vessels, which can cause confusion, frustration or "human error". In Article I, frequent switching between vessels could lead the operator to incorrectly believe that he/she was monitoring vessel A while vessel B was actually the focus of attention. In Article VI the participants simply got confused and took different navigational actions when facing the same situation of identification of an unknown object at sea. Although there were no collisions in all of these consequences, safety seems to be like rolling dice. The vacuum of legal and regulatory policies creates a huge gap for the development of the concept of autonomous unmanned shipping and remote control.

The introduction of new technologies often accompanies the emergence of new work and establishment of new strategies (Woods & Dekker, 2001) but these thoughts would be difficult to be developed in the cognitive psychological dimension. Although state-of-the-art and reliable technologies were used in MUNIN and GOTRIS, these systems were designed and configured in an "old-wine-in-a-new-bottle" fashion. Beside the sociological perspective, what apparently missing is an ecological query into the nature of work (e.g., does it introduce essential changes in this work, what competencies are required for the tasks, how the design is going to support them?). In MUNIN, the shore-based bridge system is prone to serve for "navigational mental models" under the guidance of current COLREGs regulations. It simply assumes all SCC operators have navigation backgrounds. GOTRIS also revealed a similar problem that the river pilots did not really integrate the new tools into their work practices and usability issues were identified. A perfect airplane pilot does not make a perfect air traffic controller as they receive different training suited for their work. As more projects are established and developed for an area of autonomous shipping (Rylander & Man, 2016), just as Porathe (2016) wondered, shall we need a navigating navigator onboard or a monitoring operator ashore. The "old-wine-in-a-new-bottle" design approach may be very efficient in technical system development via directly moving the bridge to the shore and turning navigators to computer system operators, but it is very limited in a complex sociotechnical system. So is the psychological perspective to understand HCI. These concerns are beyond the considerations of a pure cognitive approach but they require sociological and ecological perspectives (which will be discussed in the following chapters). The findings from these projects suggest the necessity of taking a multidisciplinary approach to understand the complexities of the shipping domain that is undergoing unprecedented transitions.

5.2 Socio-Cultural Perspectives and Knowledge Mobilisation

A predominant direction in the shipping industry is to focus on the functional development of technological artefacts and its relevance to human cognitive limitations (Cohen, Brinkman, & Neerincx, 2015; Itoh, Yamaguchi, Hansen, & Nielsen, 2001; Prison & Porathe, 2007; Sauer et al., 2002; Shahir, Glasser, Shahir, & Wehn, 2015; Tian, Wu, & Yan, 2018), such as examining the operator's SA performance (Okazaki & Nishizaki, 2015; Porathe, Prison, & Man, 2014) or a usability study in a laboratory environment (Kjeldskov & Skov, 2007). Although these constructs are useful to describe the information processing stages and ground design solutions they are essentially based on this "cognitivist approach" (Vicente, 1999), which might make them less capable of explaining what actually happen in the field and accounting for those emergent moment-by-moment actions or behaviours. One well-known example is what Klein (1993) described the firefighters do in their work - they don't make decisions but just put off fires. Another example is that many accidents investigators used "lack or loss of operator SA" as the cause to explain "human errors" (Samantha et al., 2011), which might bring obstacles to better focused research (Flach, 1995b).

An important lesson that was learnt in HCI research is that it is meaningful to go to the actual field to observe how workers are interacting with each other and how the machine is mediating their activities. Treating technologies isolated from the context in which they would be used won't help us to understand the social world (Flach & Voorhorst, 2016). One reason is that tools themselves are intrinsically culturally shaped artefacts, reflecting and influencing the social reality of the workers in their own working environment. This is a social-cultural perspective on *tool mediation*, explained by Kaptelinin and Nardi (2006):

"First tools shape the way human beings interact with reality...Second, tools usually reflect the experience of other people who tried to solve similar problems earlier and invented or modified the tool to make it more efficient and effective. Their experience is accumulated in the structural properties of tools, such as their shape and material, as well as in the knowledge of how the tool should be used. Tools are created and transformed during the development of the activity itself and carry with them a particular culture – the historical evidence of their development. So, the use of tools is an accumulation and transmission of social knowledge. It influences the nature of external behaviour and also the mental functioning of individuals (p.70)."

Such perspectives informed by Activity Theory (Leont'ev, 1978, 1981; Vygotsky, 1978) that considers technological artefacts as mediators of the workers' actions, has tremendous impact on the development of HMI (Bødker, 1990, 1991; Kuutti, 1995; Nardi, 1996). This has been substantiated in Chapter 2. With more intelligent systems introduced to the shipping industry, it is important to explore the impact of mediating technologies in operational and management practices. Article III and IV used the context of EE to explore these social dimensions.

Article III examined the practitioners' interactivity towards EE as well as the role of an energy efficiency monitoring system. The results have suggested that building a common ground is a crucial step towards their joint activity, as the engineers and navigators must understand each other's concerns in order to plan adaptively and perform efficiently for improved EE. Knowledge sharing for a mutual understanding onboard ships is very important. But what would be the role of mediating technologies in this picture? The results in Article III suggest there is an opportunity for interaction design: by taking the distributed cognition perspective, the tool may shape a discussion space between the bridge and the ECR to facilitate their collaborative learning activities. This explains the answers to the RQ2 regarding how the social-cultural perspectives perceive human-technology interaction as well as how design could influence the social-cultural aspects of work. Collaborative learning can provide opportunities to improve, evolve, reinforce, and even innovate practices (Wenger, 1998) and invite mutual learning as collectively shaped activity (Lundin, 2005). Post-journey reflection among the ship's crew is one practice example yet to be undertaken. Based on the analysis presented by the energy monitoring system, the engineers and navigators may address each other's concern and innovate together to improve their future performance in joint activities. Interaction design in such a context may likely influence communication and existing social boundaries between different divisions of labour in an organisational context (Viktorelius, 2017; Viktorelius & Lundh, 2016) (which are even described as the "Berlin Walls" in Kataria, Holder, Praetorius, Baldauf, and Schröder-Hinrichs (2015)'s studies). In fact, employing technologies to facilitate knowledge mobilisation and social interaction is a key aspect of interaction design in complex sociotechnical systems (Lundin, 2005), which has not been addressed that much in maritime human factors research or industrial development.

Article III and IV have extensively discussed learning and knowledge mobilisation in human activities and its connection to interaction design. Informed by Vygotsky (1978)'s theory, the "mind" is intrinsically social and embedded in the interaction. Our cognition is distributed and our knowledge is maintained and improved by such interaction. This is in harmony with the philosophy of pragmatism (James, 1907; Peirce, 1878) and symbolic interactionism (Mead, 1934) that the meaning of the things or the goals that make people act on reality has its profound root in social interaction. A social-cultural approach should be appreciated to understand learning and tool mediation. Learning could be conceptualized as situated action that is inherently integrated with human activities in certain context (Lave & Wenger, 1991; Wenger, 1998), opposed to the traditional classroom learning. The goal of interaction design then becomes to buttress communications and participation of practitioners, i.e., "shaping a communication space" (Winograd, 1996). The social-cultural perspective has also enabled us to conceptualise knowledge with a new perspective in contrast with the traditional view of treating knowledge as merely an object. If knowledge can be framed as "the result of everyday interaction", as it was described by Parent, Roy, and St-Jacques (2007), then interaction design is associated with knowledge transfer per se. Consequently, applying knowledge is about adaptation from one context to another, so a tool's design should support this adaptability.

Having explained the social-cultural perspectives in a theoretical discourse, Article III and IV tried to illustrate how to "think small" and "think big" in terms of human-technology interaction. The empirical data from Article III provided a foundation to understand the local issues, from the perspective of the user requirements to approach potential design solutions that may address the observed problems in the sector of energy efficiency in shipping. Parent et al. (2007) interpreted the mediating technology rather narrowly that it was generally only associated with the *disseminative capacity* that is to diffuse knowledge through the network. In the context of energy efficiency in the shipping domain, when the crews are reflecting upon the energy performance in a communication space shaped by the tool (if the crews are using the tool after the voyage), involving each other to assimilate and apply knowledge for voyage planning in the tool, and optimising navigational strategy based on dynamic energy performance monitoring supported by the tool, technology has already been implicitly associated with the *generative capacity* and *absorptive capacity*. For example, big-data based energy performance monitoring programmes have the possibilities to provide sufficient resource to enable EE performance self-evaluation and prediction in real time, so the navigators can optimise navigational strategy adaptively. Then the programme can respond the operational changes and fine-tune the prediction curve as a foundation of further decision making. Knowledge is not something hard-coded in the software (e.g., traditional expert systems), but manifests itself in the dynamic interactions between humans and machines, between machines and environment.

Both Article III and Article IV have extended the discussion at the organisational level to "think big" to reflect upon the design possibilities and management practices. Winograd and Flores (1986) defined design as "interaction between understanding and creation" (p. 2). Compared to Carroll, Kellogg, and Rosson (1991)'s notion of a task-artefact cycle, they addressed the impact of design in a broader context, i.e., "how a society engenders inventions whose existence in turn alters that society." Part of this vision is to address how design could influence not only the groups, but also the management and organisation, about innovation and communication policy of the firm and overall performance (Clay & Miller, 2002; Hertenstein & Platt, 1997; Rothwell & Gardiner, 1983).

Article III has described the organisational issues in the EE context. One major problem with many shipping organisations is that management does not have sufficient knowledge or an effective monitoring mechanism (Johnson & Andersson, 2016). The fuel management system used onboard serves as one crucial medium to link design and management. Considering knowledge transfer can be impacted from organisational level (Víctor, Natalia, & Isabel, 2012), Article IV has further discussed the emerging shift in knowledge management under the sociotechnical impacts in the knowledge-creating value network (Büchel & Raub, 2002). For example, big data is essentially concerned about new ways of management (Rødseth et al., 2016; Viktor Mayer-Schönberger & Cukier, 2013). The current EE practice improvements are mainly based on personal interest and traditional organisational training that targets individual improvement. With the data-driven decision support/post-voyage analytical systems, not only the ship's crew could have concrete platforms to self-evaluate performance, but also the management could have possibility to see what is really going on to prepare any organisational adaptation. It is critical to understand human-technology interaction from the perspective of how design can influence traditional management practices (Clay & Miller, 2002).

The context of the maritime sociotechnical system will be influenced dramatically by artificial intelligence that is, in many ways, creating a completely new era of technology and society (Viktor Mayer-Schönberger & Cukier, 2013). It will change some fundamental ways of how organizations and governments make decisions (PwC, 2016). When the local knowledge is institutionalised with proper organisational support mediated by technologies, what emerges is a synergy between humans (sharp-end and blunt-end) and technologies (data-driven decision support systems). The design of IT systems should share the sociotechnological concerns to smoothen knowledge transfer and allow safety, efficiency and effectiveness to be continuously improved in collaborative ways. The impact can go way beyond the organisational level but an industry and society level, e.g., suggesting new approaches for IMO to optimise regulations and policies regarding energy efficiency in a more adaptive manner. Although it could be argued that there is literally no panacea for all shipping companies in terms of energy efficiency, at least it makes queries into *standards* for use in organisations and how to resolve the issues in regulatory progressions. For example, Ship Energy Efficiency Management Plan, SEEMP, has been identified as one of many problems in management system standards (Johnson, Johansson, Andersson, & Södahl, 2013). Up to this point, the focus of human-technology interaction in the social dimension has been developed from "socio-cultural" to "system" (a collection of parts which interact with each other to function as a whole (Kauffman, 1980)), suggesting a socio-cultural system's connection with a larger *ecological* context.

5.3 Holistic Thinking

5.3.1 Ecological Concerns

First, we researchers may "zoom in" to see a specific design issue, as it was described in Article I and VI about the unmanned ships' SCC, to understand the problems at a micro-level: When an operator interacts with a system in a closed loop (e.g., using the system to remotely monitor the vessels), the effectiveness and reliability would highly depend on the situation analysis at the input end of the decision making process, i.e., what Rasmussen et al. (1994) described as "measuring function" of the operator. A common misconception is that as long as we take care of the cognitive constraints of humans by using reliable technical pieces, e.g., to replace human perception in the field and provide the information to the operators that is hardly accessible in remote control, then the operators would understand what is going on and deal with the complexity. It can even be simplified to a "cognitivist approach" type of questions formulated in a dyad human computer interaction framework (Flach & Hancock, 1992), investigating which design can best account for human limitations. Article I, II and VI have demonstrated that putting reliable technological components together or directly introducing state-of-the-art digital gadgets into workplaces does not mean reliable performance of the whole system, which is a common strategy in industrial settings in shipping (RINA, 2018). The MUNIN project or GOTRIS project were just examples to show how commonly these "quick and dirty" approaches were adopted and how human factors were actually incorporated into system design. The findings suggest that the approach to exclusively focus on the human characteristics (limitations) has its own limitations. This was something described by Flach and Hoffman (2003) as "limitation-based design". It was not wrong to pay attention to human limitations for design purpose, but it is incorrect to base the entire design on limitations issues. The fundamental issue is the dyad HCI framework in which the human element and technologies are situated, describing the interaction with an emphasis on technologies matching humans' internal models. The classic approach has contributed to the growth of technology-centric views. Issues described in Article II and III mirror critical gaps on the digitalisation path of shipping – beautiful interfaces and lovely technologies, but nobody uses them. The problem is that design usually downplays the role of context in which these tools would be used. More importantly the limitation based approached paid little attention to how human operators could adapt to the environment and make sense of the situation.

Second, we may "zoom out" to see challenges and opportunities in the shipping's eco-system, as it was mentioned in Article III, IV about collaboration and design management, and Article V about growing presence of IT systems in the ECR, to understand problems on a macro-level. Holistic thinking involves understanding a system by sensing its large-scale patterns: advanced technologies are constantly adding to the workplaces to solve local problems but the regulations and policies to foster collaboration and knowledge mobilisation, or manage technologies and resources, are much lagging behind. In terms of energy efficiency, SEEMP lacks requirements on policy and performance review (Johnson et al., 2013). These problems were specifically described and analysed in Article V based on previous studies and limited literatures in this regard. In ECRs, although each manufacturer has their own standards regarding design, none would normally concern about the interoperability or user experience of practitioners working with dozens of heterogeneous products and services onboard. The findings suggest the importance of having a holistic thinking in the shipping industry's ecology, not about how to tackle some usability problems or introduce new "intelligent" IT applications locally, but why it is necessary to perceive the issue globally (within an organisation, across organisations, or even in a larger context).

Today much attention has been paid to technological possibilities to address human limitations or satisfying local needs in technology-driven projects. These projects largely ignored what kind of work and eco-system would evolve towards. Regardless of zooming "in" or "out", the aforementioned thoughts are addressing the ecological concerns, which query the nature of work and explore future research directions. Article VI indicated the potential value of shifting the dyad HCI framework to a triadic semiotic framework, i.e., "human-interface-ecology" (Flach, 1989; Flach & Hancock, 1992; Rasmussen & Vicente, 1989), via an ecological approach (Bennett and Flach, 2011; Vicente, 1999). For example, the design of the SCC needs to understand environmental constraints (e.g., how the work in the SCC is going to differ from ship-handling onboard) and think about how to map the controlled processes onto the interface (e.g., how to support the operator to identify/diagnose a problem, what resources can be available). The cognitive constraints and environmental constraints together pose demands on the work domain (Vicente, 1999) and both sides should be considered in interface design. In the SCC context, a key question is to support the SCC operators to actively seek meaningful cues and efficiently allocate attentional resources by providing affordance for actions that is relative to the situations. A means-end representation of the work domain can reflect the "deep structure" of the work (Flach & Hancock, 1992; Vicente & Rasmussen, 1992) so that the interface could become "transparent" and remote complex situations can become "visible" to the operator. This is seen as developing an external mental model to make a coupling of human operators and work domain to allow direct engagement and productive ways of thinking (Flach & Hancock, 1992; Rasmussen et al., 1994). Article V proposed a Service-Oriented Architecture (SOA) as a reference model to suggest the value of adopting an architectural view on digitalisation. Certain degree of standardisation is considered as a prerequisite to allow technologies to be better integrated and governed. The ecological implications that the research arrives at provide important research directions for futuristic system design and eco-system development in the shipping domain.

Traditional shipping is moving fast towards more tightly coupled processes in the light of autonomy and digitalisation (so that services, operations, human-machine interactions are more inter-dependent). A dominant mindset in shipping industry, when it comes to technological development in a digital world, is to review the evolution of technological trajectories and tweak the implemented systems in ad hoc projects (Rylander & Man, 2016). The regulatory support is rather reactive than proactive (Schröder-Hinrichs et al., 2013). Within this context, the ecological perspective to understand human-technology interactions can provide its own unique values than the psychological and sociological perspectives, particularly with respect to methodological insights and practical knowledge about design for innovative systems. The ecological approach employs a system-level analysis and consider the coupling of "user-work" as the analysis unit, opposed to the cognitivist approach which exclusively concerns human limitations. "Fitness" is not just about designing interfaces that can address human capabilities, but it also about shaping "human–machine system against the demands of a situation or work context" (Flach & Hoffman, 2003). In addition, the ecological approach completes those descriptive approaches which exclusively concerns what actually happens. Activity-based design (Kaptelinin & Nardi, 2006; Kuutti, 1995; Nardi, 1996), situated action (Chiappe, Strybel, & Vu, 2015; Suchman, 2007), distributed cognition (Hollan et al., 2000; Hutchins, 1995) and other descriptive approaches are significantly important to facilitate the designers to gain a deeper understanding of the users' real activities in the field, to comprehend the difference between "work as done" and "work as imagined" (Hollnagel, 2015), but pure reliance on these descriptive studies would easily expose the designers to the pitfall that were shown in the MUNIN study: the technological deployment should match the existing practices. Autonomous shipping is an emerging field in the shipping industry (Rylander & Man, 2016) but there is no SCC in the world yet. "Embodying current practices in future systems is a fundamental error" (Benyon, 1992). Good design may not be about how close it matches current activities, but how it can support future possibilities (Vicente, 1999). Flach and Hoffman (2003) also contended that it is important to consider not only experts' current thinking about a problem but also the possibility of even better approaches. It is argued that the shipping industry lacks a formative approach that can focus on the constraints and resources to solve problems, support evolutionary and revolutionary design and allow viewing the system in an technologically agnostic way. It is something essentially pertinent to the nature of the work.

These concerns not only suggest the predominant issues in the shipping industry, but also attempt to provide an understanding of human-technology interaction through an ecological lens, which explains parts of the RQ2 pertinent to the ecological dimension. With the aim to dissolve the problems like "human errors" and "automation issues" in a way to hopefully edify future design, the discussion has enabled us to further approach a holistic thinking to wonder about the relationship between humans and technologies.

5.3.2 Human Error vs. Performance Variability, Automation and Complexity

In industry, it seems rational to connect the concept of safety to the goal of avoiding "human errors". The ship domain is no exception. It is reported that 75-96% of marine casualties are caused by some form of "human error" (Rothblum, 2000). From the simple cause-effect perspective, "human errors" are usually categorized as causes (may or may not be the root causes), thus accidents happen because some key components or "defensive planes" fail (Reason, 1990). Many industrial or academic research endeavours have been put on backtracking the events of the causal chain and identify the problem in terms human limitations or component failures, leading to suggestions of more training or technological improvement to prevent the human frailties that cause accidents (House & Place, 2006; Ismail, 2017; Lane, 2017; Mitchell & Dale, 2015). Automation seems to be a good aid to reduce "human error" - this logic is plausibly straight-forward, we don't like human error, so we replace our hazard source (human) with machines or we train humans hard to avoid "human error".

Compared to the amount of attention that has been given to the negative side of "human error" and failure, there is much less research looking at the bright side – a question about why we can succeed. Forty-five years ago, Apollo 13 failed to land on the moon because of an oxygen mixing tank explosion, but the astronauts and operators used their imaginations and resources in the system to quickly adapt to the unanticipated situations and successfully fit "square pegs in a round hole" to the lifeboat to get back to the earth successfully. It is classified as most well-known "successful failure" in the history of NASA (2009). It is obvious that "deviations from normal performance" saved their lives. Similar behaviour in the MUNIN projects was observed that some operators chose to approach to an unknown object ahead because they felt it looked like a floating raft. If they were right, human lives could be saved. But imagine what if something went wrong as they were taking the risks? Wouldn't these "deviations from normal performance" usually be called "human errors"?

Rasmussen (1986) contended that "human errors are the manifestation of human variability". "Let the user finish the design" (Vicente, 1999) also seems to be an indication of the importance of human performance variability and space of flexibility left in the system. More research also suggests that performance variability is something that makes our system functions well most of the time, as workers have the capability to adapt to the situation via adjusting their behaviours to meet the local demands (Dekker, 2011; Hollnagel, 2009b; Hollnagel et al., 2006; Woods & Hollnagel, 2006). Article V described a local adaption phenomenon that engineers set up new screens or put up new post-it notes in the ECR to meet their emerging needs. If there is a local need, then the users adapt to the situation very quickly. As mentioned in previous section, the shipping industry seems to be developing predominantly in this fashion with more and more technologies being introduced onboard to fix individual problems. The industry appreciates flexibility and effectiveness, but if there is something wrong, it would probably end up with a blaming game and conclusions of "human error".

The fundamental issue is maybe people assume things go right or wrong due to different causes and do not necessarily understand the relationship between "human error" and "performance variability". If resilience is defined as the ability to sustain required operations in both expected and unexpected conditions (Hollnagel, 2012; Hollnagel et al., 2010; Rankin et al., 2014), or about "having the generic ability to cope with unforeseen challenges, and having adaptable reserves and flexibility to accommodate those challenges" (Nemeth, 2008, pp. 5-6), then performance variability is a vital factor to ensure resilience of a system (Dekker, 2004; Hollnagel, 2009a). Human adaptations actually manifest themselves in error mechanisms: errors that are associated with adaptation is in nature a behavioural process of safety boundary seeking, thus adaptations or human errors cannot be eliminated per se (Foord & Gulland, 2006; Rasmussen et al., 1994).

Article V discussed that when the industry is constantly introducing new technologies into ECR to meet the local needs, the information management problems are probably created at the same time. Things go right in the same way as things go wrong (Hollnagel, 2009a; Hollnagel et al., 2006). "The technological flexibilities that simply create burdens on the practitioners" could prevail over "the technological flexibilities that are used to increase the range of practitioner adaptive response to the variability resident in the field of activity" (Woods, 1993, p. 19).

The yin yang concept in Taoist metaphysics could be useful to illustrate the relation between "performance variability" (explorations and adaptions, success) and "human error" (human inability, failure) (see Figure 7). The traditional Chinese Taoism embraces the idea that yin and yang represent the most fundamental opposition to everything but they form unification – there is no such a thing that you only see positive or negative. It is the objective law of the natural world and the origin of the transformation of all things. They are antitheses but they share the same root, so they can transform under certain conditions: when things move towards failure, the chance of success emerges. Conversely, when things are successful, the unexpected outcome can loom. Dekker and Pruchnicki (2014)'s claim of "organizations fail because they are successful" actually could be considered as a representation of the Taoism in an applied setting.

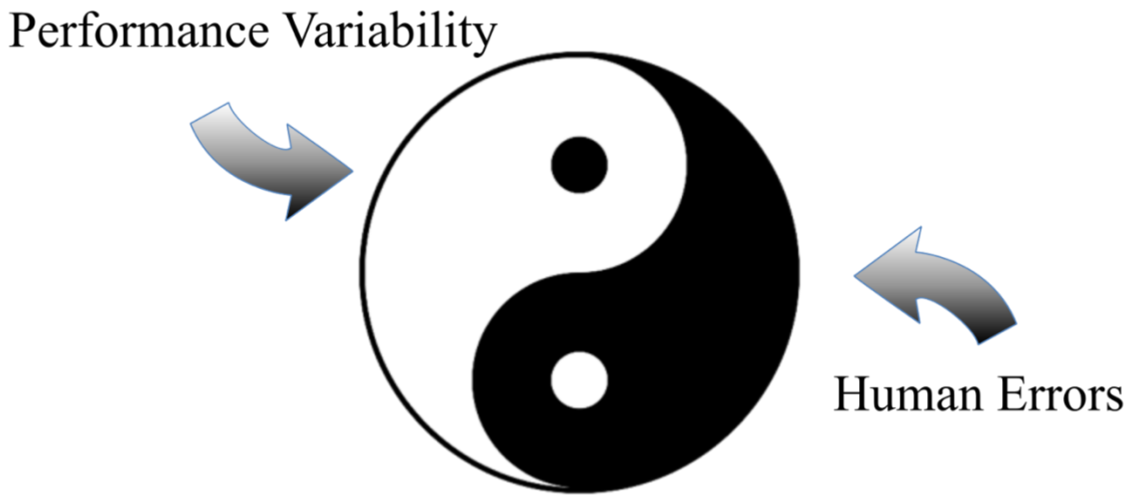

Figure 7. An inspiration from Yin and Yang in Taoism.

By taking this enlightening philosophical perspective of unification and transformation to reconsider accidents and the whole system, it might be easier to realise the limitations of the way technologies got managed or accidents were reported and understood in shipping (e.g., what functionality is required and introduce new technological artefacts, or which component went wrong and find the root cause). The insights that one can gain from hindsight bias have very limited value (Dekker, 2004). Instead, it is increasingly important to understand how a system is carrying out "transforming", or in Dekker (2011)'s words, "adaptation" or "drifting into failure" in the specific context (i.e., the slow incremental process during which period small deviations that are usually taken for granted as "norms" reverberate, proliferate, and propagate through the web of complex interactions).

In Article V, the situation in the ECR seems to be a manifestation of successful local adaptations, but local adaptiveness can lead to "illusion of assistance" or "mis-calibration" of the dynamic situation, as it might lead the decision makers to ignore the mal-adaptiveness on a global scale (Dekker & Pruchnicki, 2014). Drift is "the result of constant adaptation and growing and continued success of such adaption in a changing world" (Dekker, 2011, p. 18). The reflections from the study of ECR are congruent with this thought, accentuating the importance of having a holistic view and systems thinking in terms of human-technology interaction:

1) It is a huge risk to constantly introduce unruly technologies into our workplaces without being able to manage them from a global perspective in the first place. Today people enjoy dozens of various services and applications on their smartphones. That is predominantly because of the existence of the App Store where an ecosystem is built to connect designers and users. Focusing on infrastructural design could be an inspiration for the maritime industry to shape its own intricate eco-system in a sustainable way. The point is that the management needs to realize the limitations of this patch-fixing approach and see the big picture for the whole organisation/industry to be more "sustainable".
2) A key question regarding HCI should be asked about the "drifting" or "adapting" process – how humans can manage variability (dampen or amplify) through interface design. A fundamental interface issue is "the actor will typically demonstrate a tendency towards tight adaption" (p.125), therefore the interface must allow this boundary seeking behaviour

> through an error tolerant design (Rasmussen et al., 1994). Errors cannot be totally eradicated and the management needs to recognise the limitation of training (Chavaillaz, Wastell, & Sauer, 2016; Lundh et al., 2015; Sauer et al., 2015). The goal of HCI design should not be making decisions for the users but supporting their decision making and managing variability - how to control the effects of "human error". An alternative is to seek fault tolerance (i.e., support recover from disturbances and errors) and "look for the best trade-off between the positive and negative effects" (Alberdi, Strigini, Povyakalo, & Ayton, 2009) rather than trying to eliminate all of it uncertainties. If the management limits the performance variability to avoid failures, then it would also limit the path to success. "Human errors" is just a by-product of performance variability, which keeps the system flexible and adaptable to various conditions (Dekker, 2004; Hollnagel, 2002; Woods, Dekker, Cook, Johannesen, & Sarter, 2010). This systems thinking elucidates upon "human errors" in a very dialectical way.

One approach to do it is to couple the user to the work environment and analyse the domain and activities to alert the boundary via EID, so the operators can have direct perception of the constraints that are tightly related to safety (Rasmussen et al., 1994), e.g., "introduce indicators, pre-warnings" or "make the boundaries touchable and reversible" (p.151). An important strategy is to take the participatory approach in this process, just as Flach and Hoffman (2003) described, "cognitive systems engineering…should be part of a collaboration with engineers, operators, computer scientists, and designers in the search for qualitative insights into the dynamics of adaptive cognitive systems".

Complexities are the results of a large problem space, large numbers of interacting elements, social-cultural perspectives, heterogeneous perspectives, distributed, dynamic processes, non-linear interactions, highly coupled elements with various interactions (e.g., the element evolves with one another and with the environment) and hard to forecast or predict (Flach, 2011; Perrow, 1984; Snowden & Boone, 2007; Vicente, 1999). With the prevalence of imperfect automation today and maybe in the far future, the more exact decision it made for the user, the higher risk of automation bias and more "human errors" is introduced. This is one crucial reason that the industry needs adaptive automation that works with humans instead of substituting humans (at least today's most advanced machines have not achieved the super-intelligence to be able to think like a human). It is important to integrate human and technology into a sociotechnical system, in which their capabilities are supplementing each other to provide improved system performance - "effectiveness in sociotechnical systems will often depend on whether the technologies function as collaborative system team players" (Behymer & Flach, 2016). The most valuable systems perspective is to consider the system as a whole, i.e., shifting from structuralism, which primarily focuses on what happen inside an agent, to functionalism, which primarily focuses on what happen inside a system. The Newtonian-Cartesian decomposition thinking based on input and output of the system is appropriate for finding the causal-effect chain, but it would be intrinsically incapable of elucidating how a complex system is "drifting into failure" (Dekker, 2011) or achieving "successful failure". Maybe the ancient wisdom of Taoist philosophy from more than two thousand years ago has already informed us the nature of things in a complex world that we live in and shape, "祸兮福之所倚，福兮祸之所伏"[1] (Tzu, 600 B.C.).

[1] Translation: calamity is what blessings depend upon; in blessings there lurks the calamity.

5.4 A Pluralistic Epistemological Framework

The appended research articles present a pluralistic epistemological description of human-technology interaction. It does not only consider human capabilities, but also artefact and domain tasks. Some studies adopt the psychological school of SA interpretation to "zoom in", while others study employs social-cultural and ecological lenses to "zoom out". To some extent this thesis discourses a dialectical dialog between somewhat contradicted theories and views, between mind and matter, between the old school and new school of HCI research paradigm (embodied in Chapter 2).

Here I can take a more philosophical attitude to understand the "controversy" and value of pluralism. The debate on metaphysical theories or ontologies informs us, actually, there can be multiple ways of understanding being. The materialism advocates that matters exist independently of thoughts (Marx & Engels, 1845). The world is out there waiting to be "discovered" and the observer has the possibility to take an objective distance between him/herself and the observed phenomena so he/she could take an objective stance towards the nature of matter - this is described as the "discoverer epistemology" by Flach and Voorhorst (2016). The discoverer could be considered as a "detached observer" (Winograd & Flores, 1986) - the objective reality exists in the rationalistic view in which a cognitive agent perceive cues and forms mental representations (i.e., knowledge) that can be manipulated (i.e., thinking or cognitive activity). This philosophical ontology with the "discoverer" attitude dominates the mind-set of many scientific researchers of multiple disciplines such as chemistry, biology, physics and even computer science. Positivism asserts that there is absolute truth about knowledge and it is gathered from the natural and social world only through rigorous unbiased empirical methods, methods based on hypothesis and empirical fact gathering (O'Leary, 2007). This epistemology indicates that we should already have assumption and knowledge. Perhaps the most used research paradigm in the shipping or HCI domain is to formulate a falsifiable hypothesis and do the controlled experiment to test and observe so study could become "scientific" per Popper (1959)'s hypothetical-deductivism (falsification) principles.

But is there always absolute truth of knowledge? Is the study to our mind always subject to laws and theory? Probably positive answers for neuroscience as it is still trying to seek the objective reality in the human brain's structures, but in other cases findings might be no longer independent from the observers. Flach and Voorhorst (2016) describe the concept of "inventor epistemology" and that observers immerse themselves intimately into the studied phenomenon and knowing that can only be "invented from inside". Different observers may create different observation's results, similar to "observer's effect" in quantum mechanics (Squires, 1994). From the epistemological theory's perspective, this is congruent with post-positivism that rejects the assumption that there is an absolute truth about knowledge (O'Leary, 2007). The world is rather complicated and hard to predict, thus the *authentic* accounts of the reality can only be constructed through our interaction with the world itself (e.g., see constructionism in many social science research to understand the socially constructed nature of real-world phenomenon (Latour, 1996; Orr, 1996)).

The problem in our scientific research concerning the topic of human-technology interaction is that researchers usually take a dualistic ontology for granted in which mind and matter are deemed as two distinctive systems and therefore we have two kinds of realities or even sciences (Flach & Voorhorst, 2016). The consequence is that we might end up observing and understanding the world exclusively through one lens. Many academic debates have been unfolded around this, e.g., "mind versus matter" topic in cognitive science, especially surrounding those well-known constructs such as situation awareness. While some argued the importance of studying cognitive constructs (Endsley, 1995b), others believed the importance of focusing on the "system" (Dekker, 2011).

However, there is an alternative by looking at the actual consequences and considering the practical effects of the objects (i.e., knowledge, concepts, meanings, and beliefs). Pragmatism that derived from the work of Peirce (1905), James (1907), Mead (1956), Dewey (1929), argues that values and truths are determined by utility and experience to address the problem of the dualism. For example the radical empiricism constructed by James (1976) highlights the notion of experience to eliminate the substantiality of substance and consciousness. Bennett and Flach (2011) contended that human experience is the essentially the "joint function of mind and matter" (p. 460), something that has been echoed in Pirsig (1974)'s discourse of experience of driving the motorcycle (a metaphor of technologies). Pragmatism advocates pluralistic approaches to derive knowledge about the problem because knowledge and truth is plural and contextual - "it is not ideal or a fixed conception of reality but a means for dealing with it effectively" (O'Leary, 2007, p. 206). Winograd and Flores (1986) contended that cognition should be viewed as "a pattern of behaviour that is relevant to the functioning of the person" (p.71) and "knowledge is always the result of interpretation, which depends on the entire previous experience of the interpreter and on situatedness in a tradition" (p. 75), so knowledge is both subjective and objective. The philosophy of pragmatism invites multiple methods and worldviews to discuss the meaning of interaction and understand the nature of human-technology interaction. Perhaps there are no separate realities or sciences but one unified science ("science of experience") in which human experience is shaped in the interaction of mind and matter (Flach & Voorhorst, 2016). Pure objectivity can never be achieved (Patton, 2002) and we are part of what we aim to change (Flach & Voorhorst, 2016). What matters for researchers and designers in HCI, in order to understand the complexity of the domain, is probably a pluralistic epistemological framework in which we are not necessarily "bound to a stance" but we learn to "appreciate each stance".

From psychology, to sociology and ecology - the author's Doctoral research presented in this thesis has been generally progressed towards this philosophical stance, a pluralistic epistemology. The research is trying not solely investigating the measurements. This is critical to mature the understanding towards human-technology interaction and this complex world by not divorcing the artefact from its use context. Researchers usually consider the notions like aesthetics as "non-scientific" factors or what Norman (1994) described as "soft sciences" (that rely on subjective measurement and evaluation), because the scientists who work with "hard sciences" (that rely on precise and accurate measurement) believe they are biased. Norman (2004), in his emotional design research, points out that beautiful things might perform better. "Things that cannot be measured play no role in scientific work and are judged to be of little importance", which is a danger recognised by Norman (1994, p. 15) for research. What this thesis advocated is that we should have a pluralistic epistemology to study and understand human-technology interaction, i.e., recognising the value of both "hard sciences" and "soft sciences", both "think small" and "think big", both "zoom in" and "zoom out". A multidisciplinary endeavour has indeed contributed to the development of this philosophical stance, and can further be enhanced through an interdisciplinary stance.

In addition, this thesis not only benefits from the multidisciplinary approach, but also arrives at interdisciplinary understandings by reflecting and synthesising links between dimensions and sheds light on the future research (see Figure 8). For example although the study largely departed from the psychological school to look at the cognitive constraints of SCC operators, it arrived at organisational and sociological queries as well as ecological lessons, which are very relevant implications beyond what the cognitivist approach could provide. The social-cultural exploration about how a decision support tool could facilitate collaborative learning also motivates us to wonder about the whole human-technology system, how knowledge network may shift in future, and how the collaboration between humans and machines would evolve towards in the emerging data-driven era. The crucial value of a multidisciplinary approach is perhaps helping us to set a foundation to form an interdisciplinary synergy as an emerging language to understand complex sociotechnical systems. This view might benefit the HCI research community and the industry with its potential implications on how to bridge the gap between theoretical research and practical design (Flach & Voorhorst, 2016).

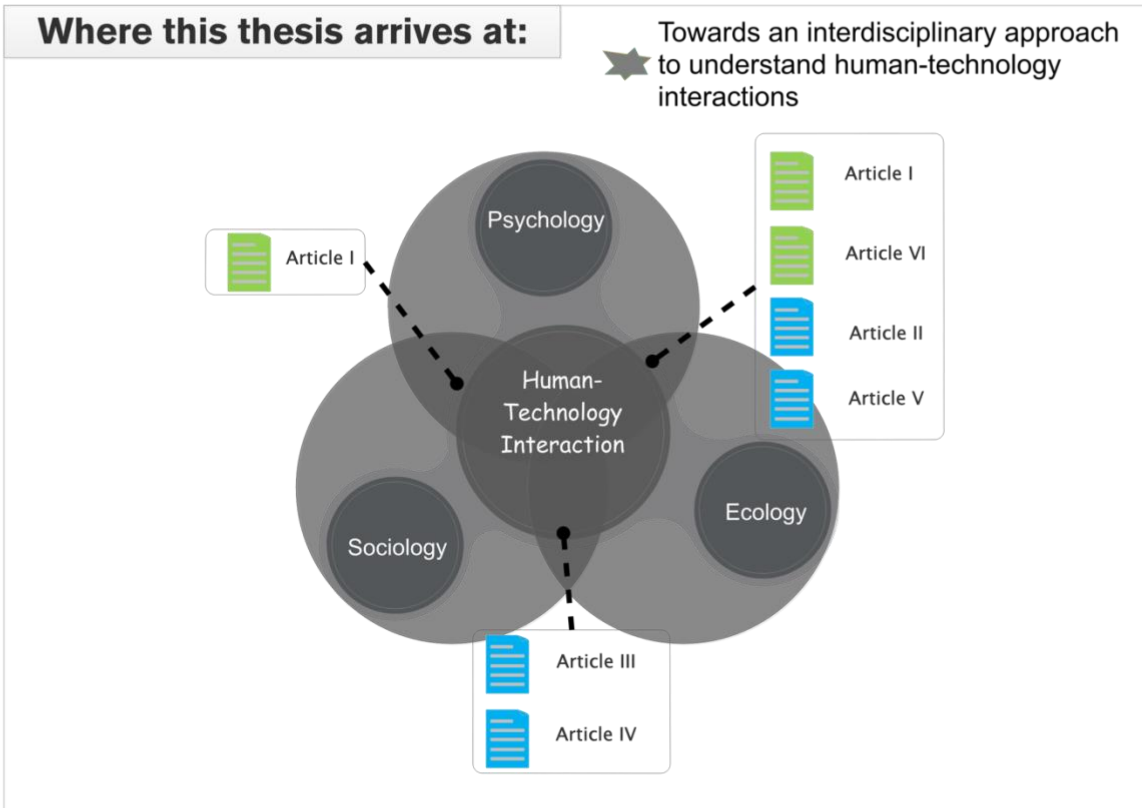

Figure 8. Where the thesis arrives at and where the future research direction should go.

Today's HCI has significantly widened its research scope to something that is situated at the intersections of computer science, social science, engineering design, and psychology. The boundaries between the traditional disciplines are diminishing (Hollnagel, 2011). The shipping industry is at full speed towards digitalisation and automation, but the transition period is, as substantiated by various studies included in the thesis, characterised of fragmented needs of all kinds, lack of human factor concerns, contextual considerations, regulatory support, and wild growth of unruly technologies. We need to move towards an interdisciplinary vision to understand and deal with the complexity of shipping, finding out better ways of design and use of technology in future research. Our knowledge and understanding need to co-evolve as our technologies advance and society progresses. The meanings of technology to our humans, either individuals, or organisations, or even the society, could not be fully understood without shifting the traditional exclusive epistemological framework to an inclusive one. Though this thesis has not produced a complete interdisciplinary framework, it hopefully has addressed the needs to develop scientific and engineering practices towards an interdisciplinary approach and provided something more the sum of the parts (psychological, sociological and ecological dimensions). In the author's opinion, it is not only the apparatus to conduct interdisciplinary research, but also this emerging language for us to learn and appreciate the complexity of the world, both industrial and societal.

5.5 Method Discussion

The combined approach of using observation, questionnaire and interview is based on the exploratory nature of the RQs, to obtain both objective performance data (such as the temporal information in Article VI) or/and subjective data (such as opinions about the tools in Article III). The shipping industry, is still rather unused to qualitative data. It is a very technology driven industry used to numerical answers and quantitative data. The use of qualitative approaches not only provide an interpretation and understanding of the real-world phenomenon (Patton, 2002), but also advocates the pluralism that even in this technology-driven industry we do have a space for qualitative research to understand the complexity of the maritime field. Reality is complex - while researchers are setting up experiments and controlling variables in the lab, they are forming a path to seek the "truth" by hypothesizing and simplification, which is essentially de-contextulisation. Positivism has tremendous value towards falsifying statements but is it the only approach when it comes to the variability within people or systems? Perhaps a quantitative approach towards finding a "significant difference" may not be appropriate to understand and explain the real world challenges and variabilities (at least in the beginning phase) as these are largely socially-constructed, culturally-rooted phenomena which will raise the type of questions that cannot be simplified to independent and dependent variables.

It should be noted that although the qualitative approach is largely used in various studies, the thesis has never intended to claim that only "discoverer epistemology" is useful or the hypothetical-deductivist approach is not important. On the contrary, this thesis has included studies that have used experimental research design (Article I, II and VI) and questionnaire techniques (customised one developed based on SART and QIUSS) for systematic empirical investigations of observable phenomena. The thesis has never intended to label qualitative research as the best research or Grounded Theory, which is commonly used in qualitative research, as the best approach. And it should not. Though descriptive statistics has been implemented, it shall be acknowledged that it is difficult to obtain statistical significance and the findings face external validity shortcomings due to the small sample size. Admittedly, a small number of participants is in no way an approximation of the manner in which an ideal research should be done, but it does not mean it will be considered of low validity for analytic and exploratory studies. It might facilitate researchers' association with the informants to support their in-depth query in a natural situated setting (Crouch & McKenzie, 2006).

Nevertheless, the ecological validity refers to the extent to which the findings of a research study can be able to be generalized to *real-world* settings (Brewer & Crano, 2000), is enhanced by the simulation environment in which the materials and setting of the study have approximated the real-world circumstances. The MUNIN project is kind of special, as there is no SCC in the real-world that the settings can approximate, which requires exploratory means to understand the emerging "field" per se. The ecological validity is also strengthened by the structural ways in which the data got "higher order of analysis" in terms of hermeneutics (Dekker & Nyce, 2004). Grounded Theory has been much used in qualitative studies to capture the emerging themes and generate explanatory propositions (Corbin & Strauss, 2008). It is important to realize that the use of the approach is rather flexible that "it can be used by researchers who subscribe to realist, objectivist assumptions as well as by those who subscribe to interpretative, constructionist perspectives" (Charmaz, 1996, p. 31) and even "researchers are encouraged to use the procedures in their own way" (Corbin & Strauss, 2008, p. x). In this thesis, the use of Grounded Theory is much concerned with generating useful knowledge and ideas, emphasising developing analytic categories and themes. Admittedly to some degree the thesis (as a whole) is lighter in constructing tightly framed theories, it still develops empirical knowledge that may later get verified through traditional hypothetico deductive methods. This reflection is mainly from the perspective of the intention embodied in the analytical processes to connect research findings to the design of future systems. To a large extent, the focus of the appendend articles is to mitigate the gap between ethnographic findings and design applicability. Letting the informants speak can be of little use but researchers need to excavate what their words mean, particularly "what informants 'need' next" (Dekker & Nyce, 2004, p. 1632), and communicate such messages to designers for future design. This is a legitimate use of Grounded Thoery, as suggested in Pidgeon et al. (1991)'s research, that researchers shall not leave the unstructured or semi-structured data interview transcripts unpacked or unanalyzed, but they shall obtain a faithful reflection of the data and faciliate possible practical improvement (e.g., show the way forward). One example is that in Article III, the author not only saturates the findings sufficiently regarding the informants' needs, but also consolidated its authenticity by connecting to both observed gaps in practice (understanding the context of navigators and engineers) and theoretical underpinnings. This sets a foundation to provide the practitioners something of high significance to design. Although it is arguable that the design implication brought up in the paper might be context-specific (thus it becomes hard to generalize partially due to the factors in the context in which the study was carried out, e.g., a specific ferry company's way of EE practice), the endeavour to translating field findings to design implications or even design innovations is rarely seen in social science studies in shipping.

The issue of "reliability" in Grounded Theory can also be questionable for researchers who are used to quantitative research. The powerful part of Grounded Theory, according to Corbin and Strauss (2008), is that it is a very structured method which gives a "traceability" of the codes. The software programme MAXQDA used in the thesis could track back how the memos evolve throughout the analysis to well support this property. The author and a SME had navigated through the different coding opportunities and the SME did not have disagreement with the author's interpretation. The "reliability" issue might also be understood from a philosophical stance - Grounded Theory's underlying philosophy of knowledge is pragmatism, which emphasises the actual consequence or effect of concepts or meanings. One core feature of pragmatism is fallibilism that empirical knowledge can be accepted even they cannot be proved with certainty (Putnam, 1994) because it is something lying in one's consciousness, embodied in the reflective thought. In the practice of Grounded Theory, one needs to feel his/her way through the process (Corbin & Strauss, 2008). This is opposed to Cartesianism that researchers better retain from making reliable and truth claims only if the findings are absolutely certain and reliable. The studies are not saying that Cartesianism is wrong but this thesis advocates to take a stance of epistemological pluralism to explore the complexities residing in human-technology interaction in shipping. Researchers working closely with technology-driven industries, such as shipping, are used to objective measurements and manipulations of numbers. They must also realise that the accumulation of knowledge in qualitative research, according to the pragmatists like Pierce or Dewey (1929), is forming the foundation of evolution of the individual's thought and is tightly connected to how society is about to influence us (Corbin & Strauss, 2008) and shape our experiences (James, 1976, 1977; Pirsig, 1974). That is to say, even if two researchers have generated two different sets of codes, it is not legitimate to claim that neither are reliable nor provide the truth. Or vice versa: even knowing that two people could generate the same set of codes just isn't a measure of whether the theory is compelling (Grinter, 2010). The personal experience could bias the analysis but it could also benefit the analysis as making the person more sensitive to the data (Corbin & Strauss, 2008).

This methodological reflection goes back to the discussion in preceding section about knowledge and truth: They are not ideal or fixed conceptions of reality but just serve as an approach for understanding and tackling the issues.

Chapter 6: Conclusions

This thesis has considered the impacts of technology, design issues and opportunities in various projects that attempt to increase safety or/and efficiency in the shipping domain. The disciplinary queries have arrived at interdisciplinary findings and implications about the design and use of technology as well as future research direction. Hopefully it has brought a broader view on HCI and a deeper understanding of the challenges/opportunities residing in the maritime sociotechnical systems during the current transition period. Major findings from this thesis have addressed the RQs posed in the beginning, in terms of 1) how technologies are influencing human performance and challenges for the operators, 2) different understandings to perceive human-technology interaction through different lenses in the shipping context 3) values of a multidisciplinary approach for research and development in shipping:

- The rapid advance of technologies is transforming today's shipping industry to a world with increasing automation and digitalisation where human operators likely need to work in new ways. The traditional cognitivist approaches have their values to address human constraints in information processing and usability issues. In supervisory tasks, perceptual challenges could be a prominent concern - insufficient situation awareness, vision tunnelling, and automation bias were identified as significant issues. As automation gets further complicated and powerful in functions, how to keep the operators in the loop and communicate the results to the operator in a form that is compatible with the operator's perception-action cycle and decision making strategy is critical to their performance. But these approaches might have certain limitations by ignoring the social environment and ecological context.
- Relevant perspectives of Activity Theory, distributed cognition and situated learning have high reference value in maritime human factors research that can inform us the nature of knowledge and interaction design in the shipping domain. Interaction design is essentially shaping a space for workers or/and management to learn and collaborate, which has the potential to influence organisational decision making and structure. It provides an important direction for future system design and research. Particularly, tool mediation plays a critical role in the process of knowledge mobilisation. Knowledge should not be simply treated as an object to cause cognitive change in the head, but a by-product of increased participation and interaction in the communities of practice. The system design should share the social-cultural concerns to explore how to situate practitioners, management and advanced technologies in a system-wide "collaborative work" and thus allow safety, efficiency and effectiveness to be continuously improved in collaborative ways. The social-cultural perspectives on knowledge mobilisation and interaction design is essential for shipping, which is generally a conservative industry driven by advanced technologies but tangled with traditional cultural context and lacking sufficient regulatory support.
- The limitations of cognitivist approach and designing only based on existing human practices could be better understood in the ecological sense. The introduction of technological artefacts has profoundly changed the work domain that the traditional dyadic "human-interface" framework is of limited value to account for the growing complexity in the field. A triadic "human-interface-ecology" HCI model might be appreciated to analyse the work domain constraints and provide design implications, which could be a valuable research direction for futuristic systems development in shipping. The research should not

downplay the context in which human uses technologies. With the introduction of more advanced technologies into workplaces, it is of significant importance to understand the nature of the work that is undergoing a transformation in order to mature our understanding of automation and interface design. The notion of ecology in this thesis also attempts to depict the problem in the eco-system that our shipping industry is facing - an increasingly digitalised, fragmented, complex working field where adaptive performance for dealing with contingencies are required from the sharp-end. The "drifting into failure" perspective or the philosophies of Taoism are enlightening by shaping our understanding of the fallacies of "human errors" and organisational failures. A global perspective is required for organisations to focus on the system performance and the Newtonian-Cartesian decomposition thinking may be deemed inappropriate to manage such drift. Instead, a holistic thinking is necessary to consider how to integrate human and technology into the sociotechnical system as a whole so their capabilities are supplementing each other to provide improved system performance.

- The thesis has used various maritime projects to explore the value of a multidisciplinary approach to form a deeper understanding of human-technology interaction. To enrich the coupling between humans and computerised systems in industrial development, we need to go beyond cognitive psychology in classic HCI and consider multiple aspects in sociotechnical systems. The thesis has illustrated how psychological, sociological, ecological findings and implications could be interconnected and synthesised beyond disciplinary boundaries, forming a deepened comprehension towards an emerging interdisciplinary language of sociotechnical systems. Although connected perspectives cannot equal to an interdisciplinary approach, it does indicate the importance of conducting interdisciplinary research to establish a coordinated and coherent whole body of knowledge. In a modern society today, the disciplinary boundaries in HCI are quickly diminishing (Hollnagel, 2011) and it is important for the contribution to be multiple, combining cognitive, social theories, methods and knowledge (Wilson, 2014).

Although the context of this thesis is the transportation sector, the reflections over humans and artefacts could well transcend the boundary of the domains. Technologies are interacting with our society with a much wider scope of audiences in a reciprocal manner. With the advent of the age of artificial intelligence, advanced technologies are shaping our social interaction and values in a way that that is difficult to predict and foresee. Simultaneously newly developed artefacts are impacted by our social structure. In many cases, people serve technologies instead of the other way around and people get frustration with technological complexity and human incapability (Norman, 1994). Laboratory experiments may not be capturing the complexity of the environments where technologies are deployed and employed, while explorations of human performance in real contexts is critical to direct future development of human factors approaches (Burns, 2017). In dealing with continuing estrangement between humans and technology, a pluralistic epistemology plays an essential role in modern interdisciplinary HCI/HMI research. One ultimate formality perhaps is the integration of the disciplines of humanities, cognitive sciences, social sciences and computational, statistical and engineering disciplines. It is critical to develop a long-term human-centric vision regarding design and technological innovation in the process of information and digital revolution, which would expectedly contribute to safety, efficiency, effectiveness and sustainability in the long run. These are very important for the shipping industry that is in the transition period. The management and regulatory guidance/policy making should involve more collaborative efforts from researchers of maritime human factors to realise the impacts of technologies on the work. Hopefully, this thesis has created a momentum for both a push and a pull, and initiated that leap of knowledge and faith.

Chapter 7: References

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