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Tiantian Zhu

Doctoral thesis

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Thesis for the degree of
Philosophiae Doctor
Faculty of Engineering
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A concept of information-based strategies for accident prevention

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Trondheim, December 2022

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“The world is my world: this is manifest in the fact that the limits of language (of that language which alone I understand) mean the limits of my world.”

By Ludwig Wittgenstein

Preface

This thesis has been prepared in partial fulfillment of the requirement for the degree of Doctor of Philosophy at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The PhD work has been carried out at the Department of Marine Technology (IMT) at NTNU starting from September 2017. My main supervisor was Professor Stein Haugen from the Department of Marine Technology, NTNU. Professor Yiliu Liu from the Department of Mechanical and Industrial Engineering, NTNU, was the co-supervisor from the beginning of the PhD period. Dr. Xue Yang was appointed as my co-supervisor also in October 2019 when she worked for Safetec Nordic AS. Dr. Xue Yang continued to be my co-supervisor after she became an associate professor at the Dalian Maritime University in the late of 2020.

The main funding of my PhD program was from China Scholarship Council. The funding period was from 27.03.2017 to 26.03.2020. There was extra financing from the Department of Marine Technology, NTNU, during the period of June 2018 to March 2020. In addition, several part-time jobs during the PhD period provided extra financial support.

Tiantian Zhu

Trondheim, August 2022

In memory of my supervisor Stein Haugen

It is quite a grief that I need to write this memorial before I get my PhD degree. I thought I could be able to have many interesting discussions with Stein far into the future of my career. Friday evening, 24th of June 2022, my supervisor Stein passed away suddenly on the way to his cabin from the grocery store.

The passing of Stein is difficult to accept. We had just had a physical meeting Tuesday afternoon, the same week when the tragedy happened. In the meeting, we discussed how to address the committee's comments to my PhD thesis, and I promised to send the revised thesis to him at a later time. He looked healthy, positive back then. There was no way that I could believe such a tragedy being real until I saw the death notice released at Safetec, where Stein worked. Since then, my tears ran down whenever I thought about Stein.

Stein had been my supervisor for the last 7 years, for my specialization project, master thesis and PhD degree. I got to know Stein when he was a professor at the Department of Production and Quality Engineering at the Valgrida Campus of NTNU, where he was responsible for the master level course Risk Analysis, while I was a master student of the RAMS program at the same department. His rich knowledge, warm smile and wisdom made him a very popular teacher among students, including me. In June 2015, Stein brought me into the MIRMAP research project from where my journey of research began. In 2017, I followed Stein to the department of Marine Technology for my PhD degree. He remained being my supervisor, even after he quitted the professor position from NTNU in the autumn of 2021.

During these years, we worked on many interesting topics including major accidents, modelling operational risk, major accident monitoring/prediction, uncertainty, decision-making, risk information, and human factors, with a focus on the process and maritime industries. Those works provided new knowledge and new tools for risk analysis and safety engineering. The research experience with Stein enriched my understanding and knowledge extremely. I believe the gains from those years under the supervision of Stein will provide foundation for my future career.

Stein is my role model. Along my journey of learning how to be a researcher, Stein Haugen was the best coach. His warm supporting smile gave me the encouragement to continue my exploration on the challenging tasks. When it came to research topics, he gave me the freedom to explore things I was curious about. In the financial aspect, he provided me all that he could, with employment in side-projects. In the skill aspect, he trained me to have skills which are needed in the future, to think independently, critically and to follow the real-world phenomenon. Stein was very open to disagreements, discussions, and new ideas. He enjoyed our discussions very much where I disagreed with him sometimes. He always knew when to compromise and when to keep committed. He liked being an engineer and to make the world safer with engineering. The only complain I have for him is that he left us far too early.

Stein encouraged and inspired many people. I feel lucky to be one of them. He was loved by his students, colleagues, and family. He contributed to make a safer society by being a pioneer of Safetec, an engineer, an advisor, a teacher, a professor. I will try to be a person like him, make contributions like he did.

Tiantian Zhu

Trondheim, 7/3/2022

Summary

With wide application of sensors and digitalization for accident prevention and safety management of sociotechnical systems, distributed decision-makers rely on information supplied for their decision-making more than ever. "If we know an accident is going to happen, we can try to avoid it; if we know the risk is too high, we can try to reduce it". In other words, decisions can be made to initiate an action for risk reduction and/or accident prevention after the risk of a hazardous event is perceived through information. Following such an idea, the thesis promotes a concept of information-based strategy for major accident prevention.

An information-based accident prevention strategy involves creating a state of knowing and subsequently reduces probability of accidents and/or their consequence indirectly through decision-making, where the decision-makers are relevant actors in complex and dynamic sociotechnical systems. An information-based strategy can be considered as a new barrier for safety management and reduce risk further in combination with other barriers.

The objective of this thesis is to increase the stock of knowledge, and to devise new applications of available knowledge, that can contribute to the theoretical foundation of information-based strategies for accident prevention. This is done by investigating several issues related to risk information. The issues include:

- Need for risk information in resolving risk-related decision problems.
- Contextual factors which impact decision-makers' information retrieval, processing and utilization when resolving risk-related decision problems.
- Prediction of information needs through decision analysis.
- Accumulation and integration of information for accident prediction
- Optimal response time for threat handling that is bounded by available information.

In terms of contribution, this PhD work provides:

- A theoretical and analytical framework for a systematic elicitation of information needs.
- Increased knowledge about the roles of risk information, which are to create a state of knowing about: 1) the existence and formulation of risk-related decision problems, 2) the severity and urgency of decisions, 3) requirements and constraints of workable solutions, 4) attributes of alternatives for comparing and evaluating, and 5) rules to maintain safety or control risk.
- An overview of contextual factors that impact the human decision-making activity, especially information retrieving, processing and utilization on the

operation of highly autonomous ships.

- A proposed multi-dimensional approach to analyze risk-related decision problems.
- A verification of accident prediction possibility by information accumulation and integration with an accident prediction model.
- A proposed "value of prediction" model based on information value theory to calculate the optimal response time for threat handling.
- A confirmation that information produced from imperfect prediction can reduce risk, at the same time lower the risk tolerance threshold and raise the maximum response investment.

In conclusion, the thesis provides novel knowledge for more effective utilization of risk information for major accident prevention in sociotechnical systems, thus contributing to the development of information-based accident prevention strategies. For the industry, the results can be used to support the implementation of hazard detection, accident prediction and prognosis, the resolving of risk-related decision problems, the design of decision support systems in complex collective modern work environments, the design of digitalization etc. With those efforts, information can contribute to major accident prevention and risk reduction more effectively in the industry.

Key words: Safety, major accident, accident prevention, decision-making, sociotechnical system, risk-related decision problem, information, risk information.

Acknowledgement

PhD work is quite challenging. I could not be able to finish it without the support from many people, including my supervisors, my parents, friends, fellows from the Department of Marine Technology, classmates, and teachers of the courses I attended. Here, I would like to express my thanks to those people.

First, I would like to thank Professor Stein Haugen for his support, which is much more than supervision. Stein Haugen has been my supervisor since 2015 when I took the master program at the Department of Production and Quality Engineering at the Valgrida Campus of NTNU. Since then, his warm smile has always given me the encouragement to continue my exploration on the challenging tasks. He gave me the chance to pursue a PhD degree and the freedom to explore things I was curious about. Along my journey of learning how to be a researcher, Stein Haugen has been the best coach. Too sad that he passed away before I can defend my thesis. I will remember and miss him for the rest of my life.

I would also like to express my gratitude to my co-supervisors Professor Yiliu Liu and Associate Professor Xue Yang. Yiliu is a very nice and supportive supervisor. In the very beginning, he supported my funding application from China Scholarship Council. During my PhD work period, he has been very open to explore the new topics with me. I learned also from Yiliu that I should question the value, innovation, and knowledge creation of my own research work. My research work was partly guided by answering those question. I think Yiliu is the most humorous one among my three supervisors. I felt sorry that I was not able to respond timely to his jokes because I was bit slow and serious. Xue became my co-supervisor in late 2019. Since then, she had the official responsibility to supervise my work. In fact, she helped me a lot when she was a postdoctoral researcher, before she became my co-supervisor. In addition, I would like to thank Kim Hyungju for his advice and contribution as a coauthor of Article 4.

I would like to acknowledge the financial support from China Scholarship Council and the Department of Marine technology. In addition, I would like to thank Safetec Nordic AS for the part-time job offer which provided me additional income during the PhD period. Thanks go to my supervisor Stein Haugen again for the part-time researcher position he offered me after my funding was ended. Those financial supports gave me the flexibility to explore interesting research topics and the opportunity to enjoy research work. I would not be able to finish my PhD research without those financial supports.

The research period would be much boring and miserable without the people at the Department of Marine Technology. I would like to thank the research fellows, administrative and IT staff, librarians at the department for their support. I would also like to thank those who organized and attended our weekly Risky Friday seminars. There had been many interesting presentations and discussions. I learned many new things.

Thanks go to my parents. My parents selflessly supported my pursuing of a PhD degree. PhD research was more difficult and took longer time than expected. Especially due to the COVID and resultant long period quarantine requirement in China, I was not able to travel home the last 2 years. It reached a record long time for me being away from home. I hope that the COVID pandemic can be over as soon as possible. At the end, I would like to express my thanks to Jon Ivar Belghaug Knarud. He was among the first reader of several of my articles; I hope he is not the last reader. We frequently discussed many general issues for PhD students, researchers, or scientific workers. Here, I wish him to get his own PhD degree soon.

Contents

Part II Research Articles

Previous PhD Theses Published at the Department of Marine Technology

List of figures

Publications

During the PhD period, 5 articles are written. Among them, 2 are published in conference proceedings, 1 is published in Journal of Loss prevention in the Process industries, the rest 2 have been submitted to journals.

Article 1

Risk information in decision-making: definitions, requirements and various functions.
Tiantian Zhu, Stein Haugen and Yiliu Liu.
Journal of Loss Prevention in the Process Industries, Volume 72. (2021).

Article 2

Human factor challenges and possible solutions for the operation of highly autonomous ships.
Tiantian Zhu, Stein Haugen and Yiliu Liu.
Proceedings of the 29th European Safety and Reliability Conference (ESREL 2019). Presented at the 29th European Safety and Reliability Conference, Hannover, Germany. 22 – 26 September 2019.

Article 3

Characterization of risk-related decision problems.
Tiantian Zhu, Stein Haugen, Yiliu Liu and Xue Yang.
Submitted to *EURO journal on Decision Processes*. Submission date: 9th of June 2021.

Article 4

Case study of major accident to demonstrate the possibility of prediction of conditions for accidents.
Tiantian Zhu, Stein Haugen, Yiliu Liu and Kim Hyungju.
Proceedings of the PSAM 14 - Probabilistic Safety Assessment and Management Conference. Presented at the PSAM 14 - Probabilistic Safety Assessment and Management Conference, Los Angeles, USA. 16 -21 September 2018.

Article 5

A value of prediction model to estimate optimal response time to threats for accident prevention.
Tiantian Zhu, Stein Haugen, Yiliu Liu and Xue Yang.
Submitted to *Reliability Engineering and System Safety.* Submission date: 23rd of August 2021.

Declaration of authorship

Stein Haugen (S. Haugen), Yiliu Liu (Y. Liu), Kim Hyungju (K. Hyungju), and Xue Yang (X. Yang) are the coauthors of one or several articles. The contributions of each author to each article are summarized by Table 0-1. While the definitions of each type of contribution are presented by Table 0-2 in the next page.

Table 0-1 Author contributions

Contribution/Article	**Article 1**	**Article 2**	**Article 3**	**Article 4**	**Article 5**
Conceptualization	T. Zhu S. Haugen	T. Zhu S. Haugen Y. Liu	T. Zhu S. Haugen Y. Liu X. Yang	T. Zhu S. Haugen Y. Liu	T. Zhu
Methodology	T. Zhu	T. Zhu, S. Haugen Y. Liu	T. Zhu	T. Zhu, S. Haugen	T. Zhu
Investigation	T. Zhu	T. Zhu	T. Zhu, S. Haugen	T. Zhu K. Hyungju	T. Zhu
Writing - Original Draft	T. Zhu	T. Zhu	T. Zhu	T. Zhu	T. Zhu
Writing - Review & Editing	S. Haugen Y. Liu T. Zhu	S. Haugen Y. Liu T. Zhu	S. Haugen Y. Liu X. Yang T. Zhu	S. Haugen Y. Liu K. Hyungju T. Zhu	S. Haugen Y. Liu X. Yang T. Zhu
Supervision	S. Haugen Y. Liu	S. Haugen Yiliu Liu	S. Haugen Y. Liu X. Yang	S. Haugen Y. Liu	S. Haugen Y. Liu X. Yang
Project Administration	S. Haugen	S. Haugen	S. Haugen	S. Haugen	S. Haugen
Funding acquisition	S. Haugen Y. Liu T. Zhu	S. Haugen Y. Liu T. Zhu	S. Haugen Y. Liu T. Zhu	S. Haugen Y. Liu T. Zhu	S. Haugen Y. Liu T. Zhu

Table 0-2 Contributor Roles Taxonomy following the CRediT system[1]

Term	Definition
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims.
Methodology	Development or design of methodology; creation of models.
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.
Writing - Original Draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation).
Writing - Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or post-publication stages.
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.
Project Administration	Management and coordination responsibility for the research activity planning and execution.
Funding acquisition	Acquisition of the financial support for the project leading to this publication.

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[1] The CRediT system is introduced by Brand, A., L. Allen, M. Altman, M. Hlava and J. Scott in 2015 and described in their article: Beyond authorship: attribution, contribution, collaboration, and credit. *Learned Publishing* 28(2): 151-155.

Part I

Main Report

1 Introduction

1.1 Background

With wide applications of sensors on processes, critical facilities, hazards, and environment monitoring, using the collected data to ensure safety is gradually a common practice. Safety management is simultaneously becoming digitalized. Many critical facilities including ships and offshore installations are becoming remotely operated which means that the safety management is done remotely; decision-makers rely on supplied information from digital systems more than ever.

For large, complex, and dynamic sociotechnical systems, risk control and accident prevention need to be organized because the systems operate in a distributed manner. It matters not only the technological advancement in understanding the complex system and controlling risk, but also relevant actors' decision-making activities. Many decision-makers are involved to keep the system safe (Rasmussen and Svedung 2000). The decision-makers face different risk-related decision problems due to their distinct positions, responsibilities and objectives. A challenge is how to promote and ensure an effective utilization of (risk) information for the decision-makers of sociotechnical systems, to control risk and prevent accident.

All forms of adaptive behavior require the processing of streams of sensory information and their transduction into series of goal-directed action (Fuster 2004). Risk control and accident prevention is no exception. From such forms the principal reasoning that information can contribute to accident prevention. After information about risk being received and perceived, corresponding action for risk reduction and/or accident prevention can be taken through decision-making. For example, a hazard sign provides information by presenting the potential hazard, so that drivers will take corresponding action to prevent accidents.

Moreover, humans control not only which goals to achieve, but consequently also which inputs to seek and receive (Tishby and Polani 2011). Decision-makers search for information – replacing unknown by known values until enough values have been established. For example, decision-makers seek the value of risk by conducting risk analysis. At the same time, conducting risk analysis requires information, information about system behavior, accident mechanisms, historical data etc.

In addition, according ISO 31000 (ISO 31 000 2009), risk is defined as "*effect of uncertainty on objectives (safety objectives)*", while uncertainty is "*the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood*". A translation of the risk definition can be that risk is a consequence of information deficiency on safety objectives, which means eliminating information deficiency can reduce risk and prevent accidents. Therefore, there is a potential to establish a concept of information-based strategies for risk control and accident prevention.

Information-based accident prevention strategy is to create a state of knowing for relevant decision-makers in the complex and dynamic sociotechnical systems. A state of knowing can improve the decision-making quality and then to reduce the probability of accident and/or its consequence. Using operational data, a state of knowing can be produced by hazard detection and monitoring, risk influence factors monitoring, barrier status monitoring, accident prognosis and prediction. The information-based strategy can be considered as a new barrier for safety management. The functionality and reliability of this barrier implementation should also be considered in risk analysis for design and/or operational risk analysis. The proposal of information-based strategy can promote investigation of the safety information environment in organizations, information behavior in resolving risk related problems, such as how decision makers seek and use relevant information, whether their basic information needs for solving risk-related problems are satisfied, whether alarms are properly handled. The proposed concept of information-based strategy can also provide theoretical support for remote safety control and management.

1.2 Overall aim

The overall aim of this PhD research is to contribute to build up the theoretical foundation for information-based accident prevention strategies. The contribution could be made by clarifying and proposing new definitions, suggesting research premises and new questions for discussing, providing new perspective, providing new knowledge from analysis, developing new models and/or methods etc.

1.3 Research discipline and scope

The research topic in this thesis is multidisciplinary lies in the intersection of major accident prevention, decision science and informatics as illustrated by Figure 1-1.

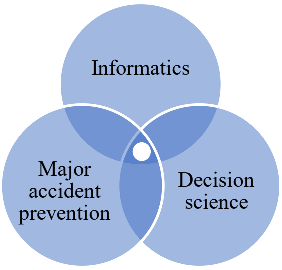

Figure 1-1. Research discipline

The scope is defined by the keywords which are used across all the enclosed articles together. Those keywords are:

- Maritime sociotechnical systems
- Major accidents
- Information
- Human decision-making

Figure 1-2 graphically presents the scope and how the 5 articles are related to the elements in the scope of this thesis.

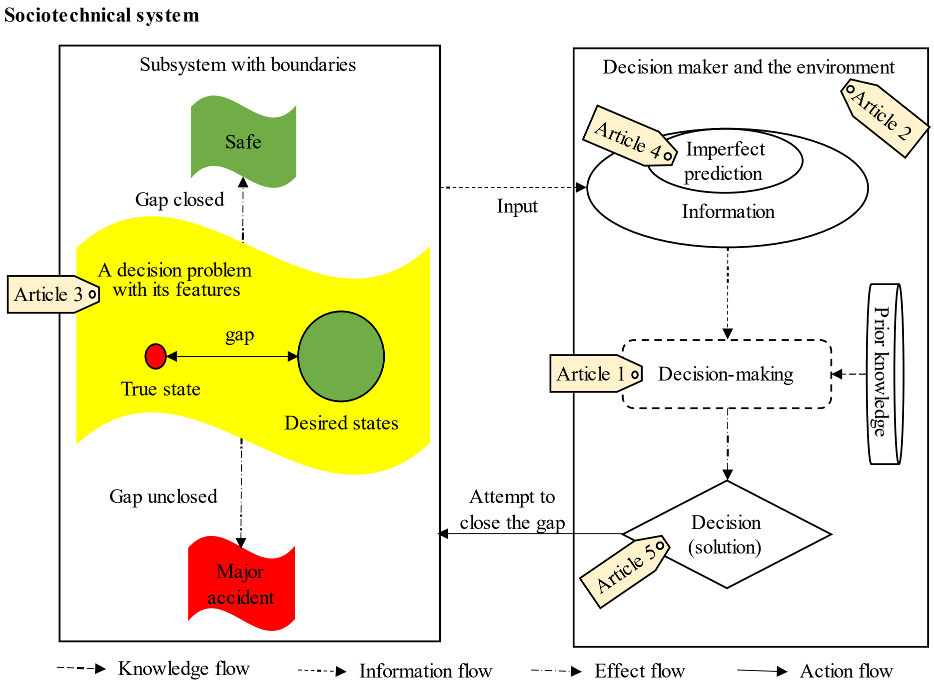

Figure 1-2. Thesis scope

Major accidents cause severe consequences which should be prevented as much as possible. Major accidents are the primary type of accidents targeted by this thesis. The focus is mainly on major accidents prevention rather than consequence mitigation. The definition of major accident from European Directive 96/82/EC applies to this thesis. Within the European Directive 96/82/EC, the definition of major accident is "*an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment covered by the Directive, and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances*"(Council of the European Union 1996).

The systems under concern are sociotechnical systems (Rasmussen 1997). Sociotechnical systems are dynamic and involve humans in multiple levels of organization and authority, technology, and their environment. In this thesis, the focus is on the sociotechnical systems in maritime sector. Major accidents are results of many unclosed gaps in sociotechnical system, as shown in Figure 1-2. To close these gaps, humans play an active role through decision-making activities. The technical and functional content of the work is controlled by "decisions (solutions)" made by the decision-makers. Overall, those decision-making activities influence the status and major accident risk of such systems.

In this work, human decision-making is looked at from a macro perspective instead of micro perspective. The latter concerns how the brain works. Thus, thinking, judging, learning etc., are not included in the study scope, even though they are important parts of human decision-making. From the macro perspective, there is a process of decision-making starting with the recognition of a decision problem and end with a made decision (solution) (see section 3.4.3 for the reasoning). The decision-maker is an information processor with prior knowledge but is also impacted and constrained by the environments. The decision-maker receives, process and actively search information to decide.

Information is "the facts and ideas that are available to be known by somebody at a given moment in time" (Zins 2007). The function of information is to create a state of knowing and reduce uncertainty. Information is a necessary input for decision-making including risk-related decision-making activities. Information is also a necessary input for risk analysis and accident prediction. Information produced from risk analysis and accident prediction is used for decision-making to produce a proper solution timely, so that the gap can be closed and accident prevented.

In total, 5 articles were developed through the PhD project. Article 1 addresses information needs from the perspective of decision-making processes. Article 2 provides an overview of different context factors which might impact the human decision-making performance, especially information retrieving and processing. Article 3 addresses problem features and provides a method to understand the features of a decision problem so that a proper decision-making process can be applied. Article 4 addresses the possibility of major accident condition prediction dependent on information availability prior to accident occurrence. Article 5 addresses how timely a decision should be made when concerned with prediction quality impacted by information dynamics.

1.4 A list of terms

A number of terms have been used in this thesis. Here, an overview of terms and their definitions is provided in Table 1-1. A detailed discussion of why some of the definitions are made is provided in section 3.2 .

Table 1-1. A list of terms and their definitions

Terms	Definition
Accident monitoring	Monitoring of the accident progression or probability of accident occurrence.
Accident prediction	A prediction about whether the accident will occur or not.
Bayesian network	An influence diagram with capability to illustrate and reason through cause-effect chain.
Decision	The chosen solution for a decision problem which is an output from decision-making activity.
Decision problem	A gap between the true state and the desired state, e.g., a deviation from norm, standard, or objectives.
Decision time	The time point when a decision is made.
Decision-maker	An agent (primarily human) who conducts the decision-making activity.
Decision-making	An activity to solve a decision problem.
Decision-making process	A general problem-solving process from problem detection to solution chosen to close the gap.
Dimension	A distinct perspective of decision problems and includes a set of problem features of the same perspective.
Dynamic risk analysis	An activity to update estimated risk of a deteriorating process according to the performance of the control system, safety barriers, inspection and maintenance activities, the human factor, and procedures.
Feature	A specific attribute of a decision problem.
Imperfect prediction	A prediction which cannot guarantee 100% accuracy.
Information	The facts and ideas that are available to be known by somebody at a given moment in time.
Information behavior	A set of activities that a person may engage in when identifying his or her own needs for information, searching for information, retrieving information in any way, and transferring and using that information.
Information need	A gap between the knowledge of the decision-maker has and desired state of knowledge to make a satisfactory decision.
Knowledge	A fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information.

Note: A continuation of Table 3

Terms	Definition
Major accident	An occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment, and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances.
Prior knowledge	The knowledge of a decision-maker before new information arrives.
Risk	Effect of uncertainty on objectives (safety objectives).
Risk-based decision-making	A deliberative decision-making activity in which decision-makers select alternatives based on the risk associated with each alternative to assure the risk is acceptable or minimized.
Risk-informed decision-making	A deliberative decision-making activity in which decision-makers are informed about the risk associated with alternatives to assure effective approaches to achieving objectives.
Risk-related decision problem	The gap between safety objectives, and the actual state of the system.
Risk-related decision	Decisions that will influence the major accident risk for a sociotechnical system, either by decreasing or increasing the risk.
Sociotechnical system	A system which is dynamic and involve humans in multiple levels of organization and authority, technology, and their environment.
Time point of response	The time point to make & accept a prediction and implement the corresponding response action.
Uncertainty	A state of incomplete knowledge.

1.5 Thesis structure

The thesis contains two parts: the main report and the collection of articles. The main report is the summarization of the PhD work. The main report is structured as follows:

- Section 1 describes the background, overall research aim, research discipline and scope, a list of terms used in the thesis and their definitions.
- Section 2 explains the theoretical research rationale and importance. It summarizes state-of-the-art and existing research results in the topics related to this thesis.
- Section 3 presents the research gaps, questions and objective, and clarification of important terms.
- Section 4 documents the overall research process, generic methods used in the PhD work, specific method(s) and process used for each research question.
- Section 5 summarizes the main research results.
- Section 6 concludes the thesis and proposes further research needs.

The second part is a collection of 5 publications which presents the results obtained during the PhD period. A list of previous PhD theses published at the Department of Marine Technology is attached at the end for information.

2 Literature study and theoretical basis

2.1 Overview of theoretical basis

The literature study contains two main parts and illustrated by Figure 2-1. The first part provides overall research rationale of the PhD work. The rationale is supported by a reasoning for why information can contribute to major accident prevention. The second part presents state-of-the-art and the theoretical basis in correspondence to the thesis scope and research aim. Research gaps are identified, and research questions are raised based on the overview.

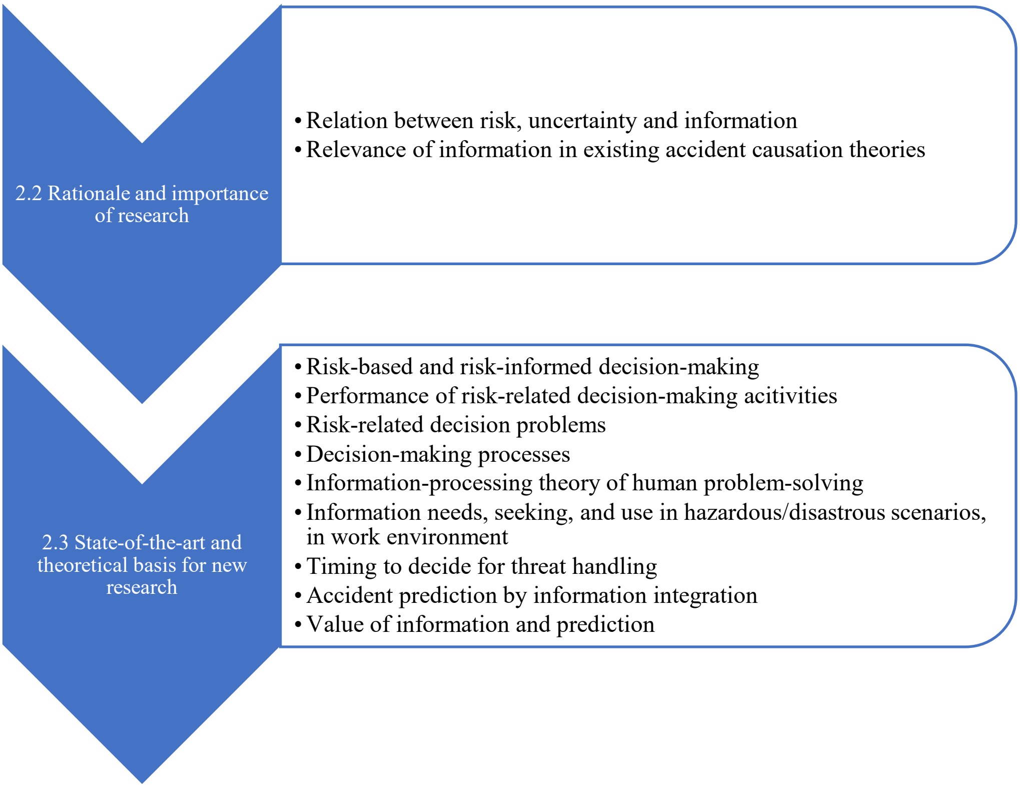

Figure 2-1. Overview of the research rationale, state-of-the-art and theoretical basis for new research

2.2 Why information contributes to major accident prevention

The reasoning for why information can contribute to major accident prevention is done from two angles. The first one addresses relation between risk and information from the definition of risk given by ISO 31 000 (2009). The second one dissects the relevance between information and existing accident causation theories. By understanding and clarifying the position of information in the many accident causation theories, the importance of improving information for accident prevention is clarified. The necessity and importance of the research topic are established.

2.2.1 Risk, uncertainty, and information

Risk has traditionally been measured as a combination of the consequences of an event and the associated likelihood of occurrence (Rausand and Haugen 2020). The term uncertainty, when discussed in the literature, mainly refers to the inaccuracy of risk measurement (measurement uncertainty) (Paté-Cornell 1996). Risk is about future. Future cannot be observed, only attempted predicted or reasoned about. Thus, there is always inaccuracy in risk prediction (prediction of consequence or likelihood or combination of consequences and likelihood of undesired events) (Sjöberg 1980). Herein, uncertainty becomes an attribute which is used to measure the variation of risk value. In this case, it is challenging to establish the relation between risk and information.

There has long been discussions about risk and uncertainty, and their relations, e.g. Finkel (1990), van Asselt, Rotmans et al. (1995), Samson, Reneke et al. (2009). In ISO 31 000 (2009), risk is defined as "*effect of uncertainty on objectives* (safety objectives)", while uncertainty is "*the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood*". Put simply, risk is a consequence of deficiency of knowledge. When uncertainty is included in the risk definition, it is straightforward to find the role of information because uncertainty is a deficiency of information, or a state of incomplete knowledge. Information has even been directly defined as "any stimulus that reduces uncertainty" by Atkin (1973). Uncertainty is a key driver of information seeking and can be reduced by gaining information (Kuhlthau 1993, Chowdhury, Gibb et al. 2014); in other words, risk can be reduced by gaining information; risk is altered when the state of information deficiency is changed. The newly established relation between information deficiency, uncertainty, and risk can be simply illustrated by Figure 2-2.

Figure 2-2. Information deficiency, uncertainty, and risk

So far, the quantifications of risk and uncertainty are not the same. Risk is still measured by probability times consequence according to the utility theory (Aven, Ben-Haim et al. 2018), while uncertainty is measured by Shannon entropy which is the extent of variability of a variable (Shannon 1948). Let's give a fire risk example to show their differences. The risk will increase if the probability of a fire accident increases from 50% to 70%, but the uncertainty about whether the fire accident will occur or not will decrease because it is more certain that the fire will occur. According to the Shannon entropy, the uncertainty is the highest when the chances of "fire" and "no fire" are 50% vs 50% for binary variables. The outcomes of fire accident and no fire accident also count in the risk calculation. An increment/deduction of risk does not mean an increment/deduction of uncertainty, vice versa.

The motivation to measure risk (obtain information about risk) is to support risk-related, rational decision-making (Zio 2018, Rausand and Haugen 2020). The uncertainty (inaccuracy) in risk estimation or prediction will increase the difficulty in solving risk-related problems.

A hypothesis can be made that the effect of uncertainty can be seen from the impact of (inaccurate/ deficient) information on decision-making. A higher degree of uncertainty will increase the level of difficulty in decision-making (Hayes, Barry et al. 2013). Let's revert to the fire example. If the chance of fire and no fire is 50% vs 50% (high uncertainty, low risk), it might be difficult to decide whether to take a preventive action or not. Instead, if the chance of fire and no fire is 70% vs 30% (low uncertainty, high risk), then it is easier to make the decision that a preventive action should be taken, so eventually risk is reduced. In this way, synchronization can be made between increment/deduction of uncertainty and increment/deduction of risk.

2.2.2 Information-processing accident causation theories

There are several theories proposed to explain why accidents happen (Rosness, Grøtan et al. 2010). Those accident causation theories do not only reflect the occurrence mechanism of certain types of accidents, but also provide a scientific basis for the prediction and prevention of accidents, as well as the improvement of safety management. In this section, the accident causation theories with strong relevance to information are to be highlighted and elaborated to support significance of the role of information for accident prevention.

2.2.2.1. An information perspective

From the information perspective of accident causation theory, accidents happen because the relevant decision-maker lacks information, due to ignorance and/or indolence about accident occurrence so that preventive actions are not taken timely. Major accidents are not sudden cataclysmic events that occur without pre-warning according to Turner's man-made disaster theory (Turner 1976, Turner 1978). Instead, there is an incubation period during which discrepant events develop and accumulate unnoticed until the accident onset. The man-made disaster theory proposes that an accident is a result of both physical failures, and failures of communicating and interpreting hazard signals and information. The signals and information for anticipating an accident are either totally unknown, or they existed somewhere or was known by someone but disregarded or not appreciated for different reasons. Thus, an accidental scenario continues to progress so that the accident is waiting to happen (Klinger and Klein 1999). Some real examples of major accidents due to certain decision-makers' overlooking risk information are analyzed by Chernov and Sornette (2016).

Wei Choo (2008) identifies three types of information impairments that could lead to man-made disasters: epistemic blind spots, risk denial, and structural impediment. These information impairments can diminish an organization's ability to recognize and respond to signals and events that presage failure. Following the information perspective, one accident prevention strategy is to make the relevant but unnoticed or ignored information become noticed and appreciated as early as possible, for instance, establishing risk monitoring and accident-prognostic schemes. Such type of accident prevention strategies will require a vigilant information culture that balances the need for efficient operations with the alertness to attend to the surprising and the abnormal (Choo 2005). This proactively prevents accidents from occurring.

For a system which is continuously running, a history of the system is created. If we agree that there is an incubation period during which discrepant events occur, develop, and accumulate unnoticed in a chronological order, it will be beneficial to introduce the idea of organization memory. Organization memory (Paoli and Prencipe 2003) keeps the record of all events which have happened in the organization including those discrepant events. Footprints of discrepant events can then still be discovered and used later for risk monitoring and accident prognosis.

2.2.2.2. A decision-making perspective

From the decision-making perspective of accident causation theory, accidents happen because of a series of "wrong choices" from decision-making activities, or "no decision-making" because problems are not recognized, thus no chance to take any action. A decision cannot be made without some information about the situation, the goals, and the possibilities of action. A lack of information may delay the moment of making a choice, and severely curtail the choice that can be made. The extent (quality and quantity) of that information may indirectly favor one outcome rather than another. Misinformation or lack of information leads to an accident through the chain of unsafe perception, decision-making and unsafe execution (Chen, Feng et al. 2021).

In a study of 100 accidents at sea, Wagenaar and Groeneweg (1987) found that most of the captains had been unconsciously running a risk instead of taking a risk after deliberate reasoning. Those captains either lacked information about the imminent danger, or did not recognize the situation as problematic, or did not foresee the negative consequences, or underestimated the likelihood of accident.

In another case, the investigation of 2010 San Bruno gas transmission pipeline rupture found out that several inappropriate decisions, which led to the rupture accident, were made independently by personnel at different levels of the organization over a long period of time (Hayes and Hopkins 2014). Sociotechnical systems have a high interactive complexity. Decisions are made in parallel or constrained by earlier actions. Human decision-makers are involved in all life phases of most technical systems, from design through construction, operation, management, maintenance, and system upgrade, to decommissioning/disposal. Risk-related decision-making activities take place from the blunt end (high-level administration) to the sharp end (operation frontline) with a high diversity in decision problems, decision contexts and decision-making behaviors. At the same time, a system's mechanisms and performance are complex and not intuitive. Each decision-maker has a model and information of a limited part of the overall problem. There is limited ability to understand, predict and control systems with more complex dynamics, like the human-climate system (Osman 2010).

Humans make decisions with conflicting pressures and needs and at the same time adapt to new conditions. Humans work between (1) the boundary of financially acceptable action, (2) the boundary of unacceptable workload, (3) the boundary of functionally acceptable action with regard to risk. Both the "effort gradient" and the "cost gradient" are likely to drive the activities towards the boundary of safe performance. An accident may occur if the safety boundary is breached. However, the decision-makers do not know how far they are from a boundary, and whether their activities will breach the boundary because the safe performance boundary is not perceivable. Thus, making the boundary of safe performance perceivable and confirmable is one of the straightforward risk control measures; in such way, decision-makers can know whether they are approaching the boundary or not (Rasmussen 1997). Producing information about the safety boundary is a step towards making it more perceivable.

At the blunt end, the classic normative theory is dominating. The classic normative theory of decision-making in risky and uncertain situations is based on economic model and logical analysis in probabilistic gambles or bets (Tversky and Kahneman 1986). The central activity is to define the outcomes and their probabilities for each alternative. The "best choice" comes automatically, which is the one which gives the highest utility. However, the normative theory is not able to describe the actual decision-making in a naturalistic world. In a natural decision-making setting, cues are ambiguous and never all presented simultaneously, problems are loosely defined, probabilities are more subjective than objective, outcomes are not able to be known precisely, alternatives are not all available or evaluated at the same time.

At the sharp end, knowledge about human decision-making behaviors forms the theoretical background of human factors. For example, the skill-rule-knowledge behavior model proposed by Rasmussen (1983) is used to understand and classify human errors and to form the theoretical foundation for the design of an ecological interface (Vicente and Rasmussen 1992). The information-decision-action flow model has been used to classify human errors and quantify human reliability (Chang and Mosleh 2007). The concept of situation awareness consolidated by Endsley (1995), Sneddon, Mearns et al. (2006) is used to understand decision-making in dynamic environments and further human errors and interface design.

The decision-making perspective of accident causation is a collection of understanding of organization behavior, human behavior, human-human interaction, human-system interaction both in temporal and spatial space. The study of decision-making should not be separated from a simultaneous study of the social context, the value system in which it takes place, and the dynamic work process it is intended to control (Rasmussen 1997, Vicente 1999). Such also makes this kind of studies challenging (Rose 1997). Accident prevention strategies stemming from this perspective include conducting decision analysis (Howard 1988) (for static tasks), risk-informed decision-making (multi-criteria analysis) (for static tasks), improving decision-making skills (Hayes, Maslen et al. 2021), setting up rules on how to make decisions, promoting safety culture, improving training, knowledge management in the organization (Choo 1991, Abubakar, Elrehail et al. 2019), establishing safety information system, and designing user-friendly human-machine interfaces.

2.2.2.3. A control perspective

The control perspective of accident causation theory says that accidents are caused by inadequate control of hazards, or more specifically: accidents result from inadequate control or enforcement of safety-related constraints. The goal of the related management is to eliminate, mitigate or control hazards, which are the states that can lead to unacceptable losses (Leveson 2004). Following this perspective, safety is defined as freedom from unacceptable losses which are determined by the system stakeholders (Aven 2022).

Control is fundamentally about information (getting it, processing it, and applying it) (Touchette and Lloyd 2000, Touchette and Lloyd 2004). To control a hazard is to 1) get sensory information about hazard status and/or status about the enforcement of safety-related constraints, 2) process the information to make it interpretable either to the computer or a human controller, 3) apply the information to make decisions to initiate a satisfiable control action so that unacceptable losses can be avoided. In addition, to be able to deploy adequate hazard control for a system, the controller should have sufficient knowledge about how the system is functioning and how accidents or incidents happen.

The relevance and importance of information in the control perspective is obvious. However, some challenges are also brought in. First, all issues related to information acquisition and processing, quality of information including its impacts in decision-making are relevant. Second, hazardous, or abnormal, situations are rare or at least less frequent than normal situations. Thus, detecting hazard signals (perceived changes of hazard status) and handling the hazard adequately can be challenging due to lack of familiarity. Third, not all hazards will materialize either. It can be challenging to say which hazard will materialize and which will not. Treating all detected hazard signals in a precautious way can lead to a waste of resources while ignoring them may lead to costly accidents.

2.2.2.4. A risk perception and awareness perspective

Accidents can be a result of poor perception and awareness of risk. Perceived risk is a predictor of demand for risk mitigation (Rundmo and Nordfjærn 2017). The term risk perception implies that risk can be sensed, if not technically then psychologically, through perceived danger or threats, or pure unknown (risk source or hazard), e.g., the sense of heavy rain (hazards) can create perception of flood risk, the sense of unfamiliar surroundings can create perception of danger due to the unknown (Carleton 2016). A simplistic view of risk perception is that it is stimulus driven; thus, to let people perceive and become aware of risk relies on information input. A more complicated view of risk perception is that it is about thoughts, beliefs, and constructs (Sjöber 1979), which means that risk perception is subjective and can be different from reality. The subjective perception is commonly a combined result of a sense of hazard, and imagination or knowledge about future outcomes of such hazard (Sjöberg 2000).

Reasonably, it is challenging to say whether the perceived level of risk is proper and how to form the right level of risk perception. So far, the level of perceived risk cannot be measured accurately. Neither is it clear what stimulus should be given nor how strong the stimulus should be to create a proper level of perception, although we do know that stimulus can create or reinforce perception.

2.2.2.5. Summary

Information impairments and deficiency plays a critical role in the many proposed accident causation theories. Thus, easing information impairments and deficiency can contribute to accident prevention. By explaining the relation between the role of information in the proposed accident causation theories can promote the recognition of information and further research on how to effectively use information for accident prevention.

2.3 State-of-the-art and theoretical basis for new research

2.3.1 Risk-informed and risk-based decision-making

Figure 2-3 outlines the research areas which emphasize the risk information as input to support decision-making activities so that risk is considered when making risk-related decisions.

Support of risk-related decision-making activities

Classic decision support using result from quantitative & qualitative risk analysis

- Risk-based decision-making
- Risk-informed decision-making

Operational decision support

- Dynamic risk analysis
- Major accident monitoring and diagnosis

Figure 2-3. Risk information and decision support for risk-related decision-making activities

Both risk-based and risk-informed decision-making (ABS Consulting 2001, Dezfuli, Stamatelatos et al. 2010, The UK Oil and Gas Industry Association 2014, Bofinger, Hayes et al. 2015, Office for Nuclear Regulation (ONR) 2017) emphasize the risk information as input for decision-making activities so that risk is considered when making risk-related decisions. Risk-based and risk-informed decision-making mainly focus on decision problems in the design phases and evaluation of alternatives.

Both dynamic risk analysis (Kongsvik, Almklov et al. 2015, Khan, Hashemi et al. 2016, Yang and Haugen 2016, Haugen and Edwin 2017, Sarshar and Haugen 2018, Sarshar, Haugen et al. 2018) and major accident monitoring and diagnosis (Park and Ahn 2010, Kim, No et al. 2015, Allalou, Tadjine et al. 2016) is to provide near real-time risk information during the operation of facilities. Those two extend risk-based and risk-information decision-making from design decision problems to operation decision problems.

Due to the hierarchy nature and distributed decision-making nature of complex socio-technical systems, distributed decision-makers are faced with different decision problems. Therefore, there will be distributed, situated, and dynamic information needs even though all decision-makers have some shared understanding of the overall system. Relevant information for decision support should be distributed and featured to fit their own needs of each distributed decision-makers (Brehmer, Leplat et al. 1991).

Thus, before any system which provides informational support can be construed, there has to be a clear account of, firstly, the activities to be supported and the information requirements for people carrying out the activity (Hall 2008, Adam 2019). The design principles of decision support should reflect an understanding of decision-making behaviors in the organization (French, Maule et al. 2009) including why and how human seeking information (Rouse and Rouse 1984, Vakkari 1999), the impact of decision support on decision-making processes (Mackay, Barr et al. 1992). An example is that decision support for one-off, static tasks is not the same as decision support for real-time, dynamic decision-making tasks (Lerch and Harter 2001, Gonzalez 2005). Scenario planning can be used as a way to provide support in a dynamic decision-making environment (Chermack 2004). There is also a need for system design to help decision makers to differentiate between the cues that are truly irrelevant and those that might be indicative of a problem (i.e., a different class of situation) (Jones and Endsley 2000).

In the area of risk-based and risk-informed decision-making, and operational risk analysis, studies focus on the best way of modelling and presenting risk using qualitative/quantitative metrics, especially output from risk analysis, such as probability, consequences, expected utility, risk matrix. The underlying assumptions are that 1) risk information is (quantitative) measurements of risk that we get from risk analysis, 2) a sound deliberation about what is the (potential) decision problem has been done; 3) the information needs are already known; and 4) decision-makers strategize and generate multiple alternatives and seek for a choice with the lowest risk or with the optimal balance between risk and benefits by comparing all alternatives. Research activities have been drifted to how to ensure the accuracy of risk measurement, and how big the error is (measurement uncertainty), if accuracy cannot be guaranteed. Other information characteristics such as relevance, completeness, and availability are less discussed. In addition, when risk information is interpreted as a measurement of risk, it violates the phenomenon that decision-makers take signals directly from the environment without risk measurement. Restricting risk information to risk measurement prevents an effective utilization of information for decision-making and accident prediction.

So far, the information needs of relevant decision-makers in resolving risk-related decision problems haven’t been addressed systematically. There is also a lack of theoretical and analytical framework for the systematic elicitation of information needs, of which the need of risk information is one kind. The lack of a thorough investigation of information needs would make the risk information support unsuitable, or not timely, or insufficient for decision-makers, and create loopholes such as those in the Reason’s Swiss Cheese Model, especially for emerging and complex systems. The lack of understanding in information needs prevents the effective supply and utilization of information. Decision-making performance can be deteriorated, and risk can increase.

2.3.2 Performance of risk-related decision-making activities

2.3.2.1 Performance evaluation

The function of information is to create a state of knowing to ensure the performance of risk-related decision-making for accident prevention. It is of importance to clear how performance is evaluated. The way to evaluate performance would impact the issues identified for research.

It is challenging to judge the decision-making performance. The judgment of "wrong choice" is commonly based on the after-myth of an accident, which is based on the outcome (whether the best, or an alternative which would have caused less severe consequence, is chosen). However, a chosen alternative at the time of making decision must be thought to be a good one or at least an acceptable one. Second, an alternative which seems proper in a short term can be wrong in a long term. Third, an alternative to ensuring "low risk" is not equivalent with ensuring "no accident". Therefore, an accident can still happen even though it is a good decision. Fourth, high hazardous systems are usually designed to have redundancy. Then one bad decision will not necessarily lead to an accident, which complicates "wrong choice" assessment post accident. Fifth, it is difficult to separate decision-making activities because we behave in a dynamic and continuous mode in real life (Brehmer 1992, Klein 1993).

There are several considerations regarding judgment of decision-making quality. Even though there is a tendency to assess decision-making quality depending on outcome (Arvai and Froschauer 2010), others have suggested to judge the quality of decision-making based on the decision-making process (Orasanu, Martin et al. 1998, Hollnagel 2007). Further, errors can be identified from each phase of the decision-making process (Dörner and Schaub 1994, Orasanu, Martin et al. 1998). Thus, Orasanu, Martin et al. (1998) proposed the two major ways in which error may arise in naturalistic decision-making contexts: (a) develop an incorrect interpretation of the situation, which leads to a poor decision -- an SA (Situation Awareness) error; or (b) establish an accurate picture of the situation, but choose an inappropriate course of action -- a CoA (Course of Action) error; Orasanu, Martin et al. (1998) further proposed that ambiguity, underestimating risk, goals conflicted, and consequences not anticipated are the main factors which contribute to those decision errors.

Hollnagel (2007) proposes that all failure modes of human action can be valid for decision-making when decision-making is considered as an activity. That is, decision-making can fail if the decision is made at the wrong time, or is made too quickly, or considers the wrong alternatives, or if taken out of order or sequence. The normative criterion of making the right decision (choosing the best alternative) can be replaced by a more detailed analysis of whether the decision is made at the right time, with the right duration, and so on, and implemented in a way which achieves the desired objectives.

Another challenge for decision-making performance evaluation comes from the fact that we cannot truly, fully understand all the reasons for what a person decides to do. Such a fact leads to an increased difficulty in erecting risk control measures. All theories about human behaviors are simplifications. Our understanding is going to change continuously. In addition, humans are adaptive and can learn and change over time. One idea is to include a form of higher-order prediction (prediction about the prediction model). A higher-order prediction should be able to predict when the model will go wrong or when human behavior will change, so we switch to a new prediction model before too many mistakes are made (Subrahmanian and Kumar 2017). Another idea is ensuring resilience (Hollnagel, Wears et al. 2015), through which the system is able to tolerate a wide range of alternatives and/or inappropriate decision-making so that accident will not happen even if mistakes are made.

2.3.2.2 Factors impacts decision-making performance

There are extensive studies in the field the human factors which evaluate the impact of factors on decision-making (Woods 1988, Orasanu and Strauch 1994, Orasanu, Martin et al. 1998, Mosier, Sethi et al. 2007, Strauch 2016) because human factors mainly studies “environmental, organizational and job factors, and human and individual characteristics, which influence human behavior at work in a way which can affect health and safety” (HSE Health and Safety Executive 1999); and human reliability analyses try to evaluate the possible errors that may be made by decision-makers in the system (Rausand and Haugen 2020). The results from human factors studies are used for the design of decision support of risk-related decision-making activities, human-machine interface design (Rasmussen 1983, Abbott 1990, Endsley 2012), instruction design, training design etc.

Even though there are many studies on decision errors and human factors, the information behavior of decision-makers in working environment or dangerous situations for risk control and accident prevention is not researched much (Chang Hoon, Jong Hyun et al. 2006, Mosier, Sethi et al. 2007, Mishra, Allen et al. 2013, Choo and Nadarajah 2014, Sarshar, Haugen et al. 2018, Navitas 2021). Information behavior is the set of activities that a person may engage in when identifying his or her own needs for information, searching for information, retrieving information in any way, and transferring and using that information (Wilson 1999). Relevant research is to address why and how problems related to any sub activity or component of information behavior of any specific group of people or under any specific kind of context, e.g., the information seeking behavior of legislators (Alfarhoud 2016).

Human errors are essentially about human behavior of which information behavior is a great part (Wilson 1981). Among those environmental, organizational and job factors which impact decision-making performance, it is also promising to see how those factors impact the information behavior in decision-making.

2.3.3 Risk-related decision problems

2.3.3.1 Diversity of risk-related decision problems

The motive to know the value of risk is to support the resolution of relevant risk-related decision problems. To investigate the use of risk information in decision-making, the premise is to know what kind of decision problems which need to be solved.

Risk-related decision problems might be directly or indirectly associated with hazards, barriers, etc. such as allocation of maintenance budgets for safety, manning levels, inspection and maintenance planning, how to repair a valve etc. Across the whole lifetime of sociotechnical systems, there are unaccountable risk-related decision problems with a high diversity. At any time, there are many problems, problems which:

- Should have been recognized but are not.
- Have been recognized and are to be solved,
- Have been recognized and should have been solved; hence are time critical,
- Are already solved but have created new issues,
- Have been solved with no further issues.

Those problems together reflect the system's safety status. In addition, the high diversity of risk-related decision problems is also due to system diversity, phases in product life cycle, accident prevention and consequence mitigation, their impacts on system safety, targeted object, and time span etc.

Some problems have high impact on system safety while others have minor impact. Those high impact problems are usually prioritized compared to those with minor impact. Some problems are relatively static (such as choose a critical component for replacement, choose a route to go) while others are more dynamic (such as driving a car, maneuver a ship, flying a fighter, operating a power plant). Static decision problems are generally (although not necessarily) framed as a single decision which takes place within a broader time frame, and which has its inputs as a fairly static description of the environment. Dynamic decision problems demand solutions across a fairly narrow time window and they are dependent on an ongoing, up-to-date analysis of the environment input (through environmental scan) to the decision-making process.

The vast diversity of risk-related decision problems poses challenges in understanding and analyze the utilization of risk information for resolving those problems. They are very likely to have different features and therefore are more prone to a certain way of decision-making. An improved understanding the problem features could be beneficial to ensure decision-making performance.

2.3.3.2 Classifications of risk-related decisions

There are several schemes to classify risk-related decision problems. Those schemes include decision settings (Rosness 2009, The UK Oil and Gas Industry Association

2014, Bofinger, Hayes et al. 2015, Yang and Haugen 2015, Burian, Kochan et al. 2017), way of decision-making (Rasmussen 1983, Orasanu and Fischer 1997), and data sources for control (Hoc and Amalberti 2007).

Rosness (2009) proposed a typology of decision settings based on two dimensions: level of authority and proximity to hazard. Following the typology, 5 types of decision settings are defined. They are: 1) political arenas, 2) business management, 3) administrative and technical support functions 4) operations and 5) crisis handling. This typology exemplifies decision problems in each class by outlining the typical and stereotype of the problems and corresponding decision-making processes. There are further studies of different risk-related decision problems in each class. Hayes (2013) studied risk-related decisions in the operation phase of process systems. Endsley (1995) focused on decision-making in dynamic environments, in which the decision-maker needs to reformulate the problem at each step and act upon it. There are also studies about decision problems and relevant decision behavior and decision support in abnormal and emergent situations which belong to the category of crisis handling (Kalambi, Pritchett et al. 2007, Argyris and French 2017).

The UK Oil and Gas Industry Association (2014) classifies risk-related decision problems into type A, type B and type C considering 3 decision context factors: type of activity, risk and uncertainty, and stakeholder influence. Corresponding way of decision-making are proposed for each type. To solve type A problem, one should follow good practice; to solve type B problem, one should conduct engineering risk assessment; while for type C problem, taking a precautionary approach is preferred. This classification is operational-oriented and provides support in how to make decisions while with a limited coverage of decision problems and dimensions.

The existing classifications do not consider the fit between risk-related decision problems and ways of decision-making. Not much focus has been given to features of risk-related decision problems either.

2.3.3.3 Features of decision problems

In the field of problem-solving and decision-making, discussions about problem types and the suitable ways to solve those problems have gone on since the 1960s. Among the earliest is the concept of complex and ill-structured problems proposed by (Newell, Shaw et al. 1958, Newell 1969) to understand the chess game. Simon (1973) continued the discussion to give a clearer idea about what are well-structured problems and what are ill-structured problems. Rittel and Webber (1973) proposed that social problems are "wicked problems" in its nature, contrary to "tame problems", thus it makes no sense to talk about "optimal solutions" of "wicked problems" unless strict satisfaction criteria are imposed first. Differentiation is also made between "dynamic tasks" (such as firefighting, driving) and "static tasks" (such as lotteries) by Brehmer and Allard (1991). Dynamic tasks require a series of interdependent decisions which must be made in real time. The states of the dynamic task change both automatically and because of the decision-maker's actions. Contrary to solving simple problems, microworld simulation is suggested to solve complex problems (Frensch and Funke 1995, Funke 2010, Fischer, Greiff et al. 2011, Amelung and Funke 2013).

However, single dimensional classification such as wicked and tame problems is not sufficient to provide guidance in problem-solving (Hisschemöller and Hoppe 1995, Alford and Head 2017, Turnbull and Hoppe 2019). There are other types of features which demand different problem-solving skills. Effort continued to assess problems in multiple dimensions, e.g., the degree of wickedness, the degree of uncertainty. Specific guidance for problems with varied features is provided afterwards.

It can be concluded that there is a development of applying a system engineering concept and design theory to look at and manage decision problems. Kreuter, De Rosa et al. (2004) applied such an approach to understand environmental health problems. It turns out that most environmental health problems are complex, dynamic, or wicked. Therefore, traditional expert-oriented and mechanistic methods of problem-solving alone are insufficient and inappropriate. Instead, the public health practitioners as decision-makers should seek transdisciplinary involvement and maintain stakeholder involvement throughout the problem-solving process. At the same time, there should be a sustainable commitment to sound toxicological and epidemiological science to discover new knowledge and to improve current solutions.

The present study about problem characterization can provide a methodological foundation and references to study features of decision problems and define dimensions for decision analysis of risk-related decision problems.

2.3.4 Decision-making process

The quality of decision-making activity is not only dependent on the chosen solution, but also on the rationale of how a decision is reached. An improved understanding of decision-making behavior can provide insight for decision support. In order to see how people come to their decisions, it is better to view decision-making as an activity (Hollnagel 2007) which can contain a set of sub activities. Information searching is one kind of sub activities (Donald 2016). Thus, studying decision-making process contribute to both quality insurance and creating new knowledge of the information behavior of decision-makers during decision-making activity.

2.3.3.1 The 5 variations of decision-making process

There are 5 major variations of decision-making processes: bounded rational decision-making (March 1991, March 1994, Simon 1997), rule-based decision-making (March 1991, March 1994), recognition-primed decision-making (Klein 1993), sensemaking (Weick 1995, Klein, Moon et al. 2006), and intuition (March 1994, Kahneman 2011).

Bounded rational decision-making process implies that decision-makers strategize and generate multiple alternatives and seek for the optimal choice or decision by comparing all alternatives (March 1994). This process requires much effort from the decision-maker in both information collection, reasoning and deliberation. When a decision-maker is facing a critical and complex decision with little knowledge, the rational decision-making process is likely to be engaged. Risk-informed decision-making is mainly studied based on the assumption of bounded rational decision-making theory (Aven, Vinnem et al. 2007, Dezfuli, Stamatelatos et al. 2010, Zio and Pedroni 2012, Haugen and Edwin 2017, Office for Nuclear Regulation (ONR) 2017).

Rules are commonly used for safety controls to guide and limit behavior in organizations (Hale and Swuste 1998). An empirical study shows that rule-based decision-making behavior is more frequent than risk-based decision-making behavior for middle managers in the oil and gas industry (Rezvani and Hudson 2021). Rule-based decision-making assumes that decision-makers decide by matching their identities (such as job responsibilities) and rules applicable to the situation and their identity (March 1991, March 1994). Both identity meanings (such as job responsibilities) and rules are established prior to taking actions. Those rules are usually established based on regulation, procedures or evidence. Making decisions based on rules is efficient, simple and accurate. Furthermore, rules are able to assist decision-makers in seeing the interdependencies and nonlinear relationships between different criteria, as well as overcoming uncertainty caused by incomplete, vague, or imprecise information (Rezvani and Hudson 2021).

The recognition-primed decision (RPD) process is proposed by Klein (1993). It describes the decision-making processes of experts in naturalistic decision contexts. The complicated version of recognition-primed decision (RPD) processes says that decision-makers (usually experts) take cues from environment, use prior experiences and knowledge to recognize patterns, identify a single workable solution, and then conduct mental simulation to see whether the solution works. If the solution works, they will just execute the solution. They do not compare multiple alternatives as described by the bounded rational decision-making process. Experienced decision-makers typically exhibit intuitive competence within their domains because they are able to quickly identify a subset of cues that is critical to the accurate diagnosis of a situation and the subsequent decision and action (Klein 1993, Mosier and Orasanu 1995, Orasanu and Fischer 1997). For example, expert pilots can look out the window and to decide the speed and descent rate to reach the runway; expert fire-fighters use the sponginess of the floorboards or the color of smoke to assess the origin and extent of a fire. Due to their rich knowledge and experience, experts are able to perform successfully in complex situations (Mosier and Fischer 2010).

Sensemaking is a problem-solving process which begins when an individual is confronted with a situation that deviates from the normal daily routine (Weick 1995, Choo 2002, Klein, Moon et al. 2006, de Graaff, Giebels et al. 2016, Kilskar, Johnsen et al. 2018). Through sensemaking, decision-makers make a motivated, continuous effort to understand connections, then use the connections to anticipate trajectories and act effectively (Klein, Moon et al. 2006). Sensemaking needs cues as triggers, such as surprises that can be interpreted as a lack of preparation, vigilance, control, or discipline in an organization. Examples are applying new technologies during operation, changes of rules or operation instructions, and other changes that create a dynamic and less predictable environment where existing frameworks for solving problems repeatedly and maintaining safety do not work (Maitlis and Christianson 2014).

Intuition-based decision-making process means that decision-makers make decisions automatically and unconsciously (Kahneman 2011). Making decisions based on intuition is fast and effective, but not possible for decision-makers when facing unfamiliar, unpracticed decision problems (Kahneman and Klein 2009, Kahneman 2011). There is a quality difference between immature (general) intuition and educated (expertise-based) intuition. Educated intuition is more accurate than immature intuition because it is a result of rich knowledge from extensive domain experience (Salas, Rosen et al. 2010). Educated intuition is applicable for regular situations in predictable system environments but not valid for emergent situations.

Many empirical studies have investigated how decisions are made in real life conditions. For example, Rezvani and Hudson (2021) explored the actual decision-making activities of middle management within the oil and gas industry. The study found that middle management are involved in various types of decision problems, 80% of their decision activities are risk related. Middle management actively attend to different steps of decision-making: framing a decision problem and clarifying the objectives of a decision or reasoning, providing a richer interpretation, unifying the decision-maker's opinions, selecting a final alternative with a desirable consensus, and final implementation and evaluation of decisions. However, they do not make decisions based on a complete set of criteria and alternatives, nor do they use mathematical and rational reasoning for their choices. Instead, they exhibit naturalistic decision-making in which middle managers search for information progressively, incorporating changes in their formulation because of new data. Equipped with knowledge and experience, middle managers recognize patterns and apply them in their decisions which finally results in a quasi-automated decision process. Rule-based decision-making process is more frequently used compared with bounded rational decision-making process. Decision-makers also chose several options at the same time in abnormal and emergencies if it is uncertain whether those alternatives could work.

A specific process can be more successful than another in certain situations. Decision-makers' information behaviors including information requirements can be different among those decision-making processes. It is of interest to investigate which process decision-makers will/should use or within what limits their process can be determined.

2.3.3.2 Factors which impact the selection of decision-making process

Substantial evidence exists to support the notion that decision-making behavior will vary depending on seemingly minor changes in the task and/or in the context (Payne, Bettman et al. 1993). Several situational factors have been discussed, such as:

- The newness, complexity and predictability of the system behavior (Kurtz and Snowden 2003, Snowden and Boone 2007), criticality of the problem; whether preferences and cause/effect relations are clear (Thompson 2003).
- Whether there are specific rules or norms for decision-making activities in the organization (such as NASA has its own risk informed decision-making procedure (Dezfuli, Stamatelatos et al. 2010)).
- The nature of the environment including the availability of information and time resources.
- Characteristics of the decision-maker themselves including knowledge level of the decision-makers and the degree of belief in their knowledge related to the decision problem.

So far, there is no analytical method to predict the possible decision-making process. Work domain analysis, cognitive task analysis, and process tracking techniques (Patrick and James 2004) are the empirical methods to investigate the actual decision-making process in resolving certain problem. Several process tracking techniques have proved valuable for observation of decision-making process, in particular, verbalization (Isenberg 1986, Rolo and Cabrera 2000), eye tracking, audio recording (Rezvani and Hudson 2016, Rezvani and Hudson 2021). Since those methods are real life observations or interviews etc. the obvious drawbacks are that 1) they are time consuming, 2) some events are rare which means they are difficult to observe, or too expensive to establish experiments, 3) the operating environment must exist first for observation. Observing and recording decision-making behavior in a simulated environment, such as a simulator, is an alternative to real life observation.

2.3.5 Information-processing theory of human problem-solving

The information-processing theory of human problem-solving proposes that humans' minds work like computers; They receive input, process the information they receive, and delivers an output, rather than merely responding to stimuli. During problem-solving, human is both an information processor and problem solver. The three components: information-processing system, task environment, and problem space, establish the framework for the problem-solving behavior (Newell and Simon 1972). Through the problem-solving process, problem solver selects actions that will alter the environment to meet goals and objectives so that the gap will be closed. In approaching the task, the problem solver forms a mental problem representation about the situation in terms of a problem space, which is her or his way of viewing the task environment.

"*The problem-solving activity can be described as searching for information – replacing unknown by known values – rather than a search to reach a particular goal. In such an activity, recognition processes play a crucial role in determining (a) when enough information is available to establish the value of another variable, and (b) when enough values have been established to reach the goal*" (Simon 1978). Saunders and Jones (1990) proposed a general, pre-theoretic model relating information flow characteristics to a dynamic decision/making process, shown in Figure 2-4.

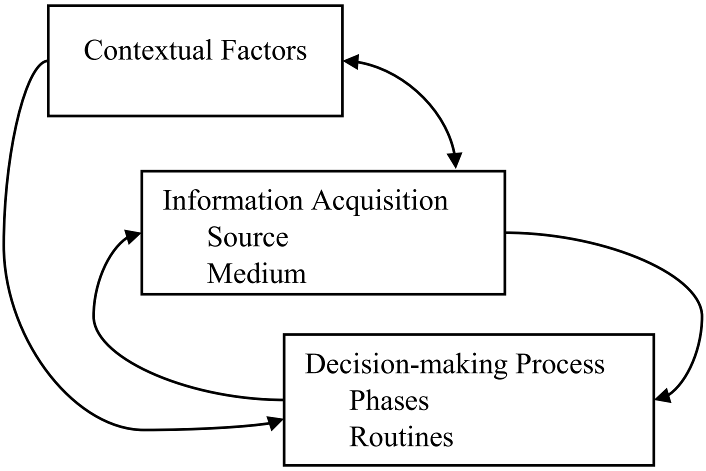

Figure 2-4. A general model relating information acquisition to the decision-making process (Saunders and Jones 1990).

According to the standard information-processing model for mental development, the mind's machinery includes attention mechanisms for bringing information in, working memory for actively manipulating information, and long-term memory for passively holding information so that it can be used in the future. Therefore, the basic psychological characteristics of the human information-processing system sets bounds on possible behavior but do not determine the behavior in detail (Simon 1978).

A decision-making process can be also regarded as a cognitive problem-solving process. An cognitive process is a sequence of internal states successively transformed by information being processed, since decision-making process model is presented as systematic sequential steps from problem-sensing to alternative-choosing, as shown in Figure 2-5. This suggests that decision-making processes may be considered as a series of activities of searching, selecting, and processing information before making a final decision while they are constrained by limited search and information-processing capabilities. In a descriptive sense, these processes delineate discrete steps in decision-making. Prescriptively, the models suggest systematic rational processes that will

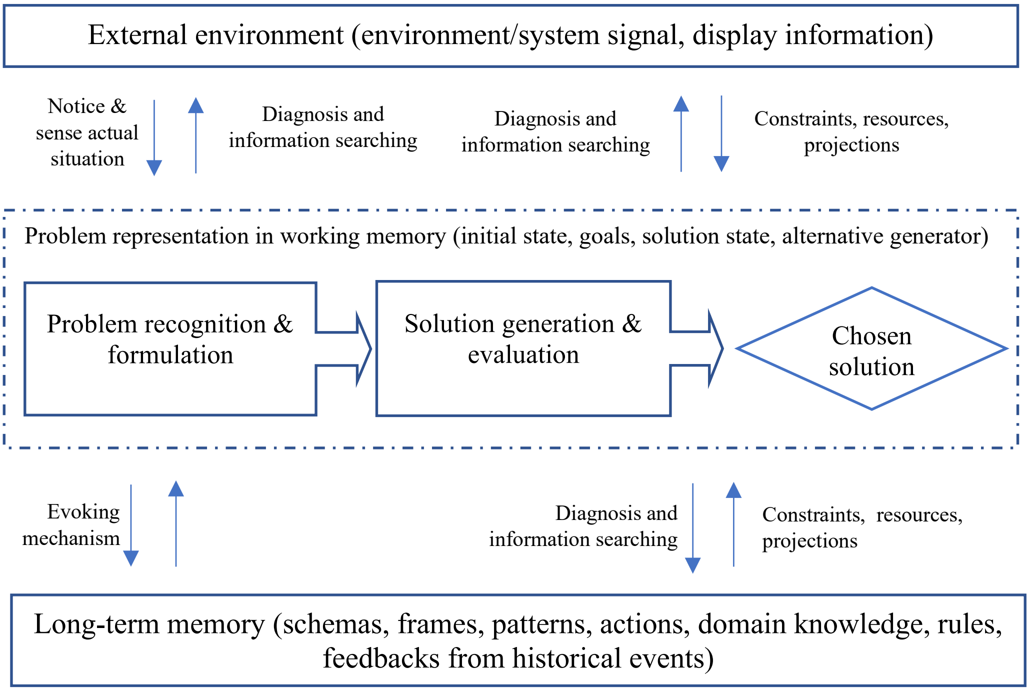

Figure 2-5. Decision-making process combined with internal and external information sources

increase the use of available information and resources and reduce error. Existing decision process models lack an in-depth study of the state of "information" during decision processes. There is no general model that explains the state of information in each phase of the decision-making processes (Tarng and Chen 1989).

2.3.6 Information needs, seeking, and use in hazardous/disastrous scenarios, in work environment

As described earlier, information and decision-making are with importance and potentials in expanding the strategies for accident prevention. The consensus is that information about risk is needed for making relevant decisions, such as in the framework of risk-informed decision-making, risk-based decision-making. The consensus is reached based on the normative practice that decision-makers should be informed about risk. To date, there is little research on professionals' information needs, how they seek for information, the use of information, the impact of their information behavior on their task performance, and whether their information environment is sufficient for their tasks when it comes to risk-related roles or scenarios in high-hazardous organizations. Figure 2-6 shows a generic information behavior model proposed by Leckie, Pettigrew et al. (1996). Studies are scattered into risk communication of natural disasters, safety management, naturalistic decision-making, emergency handling.

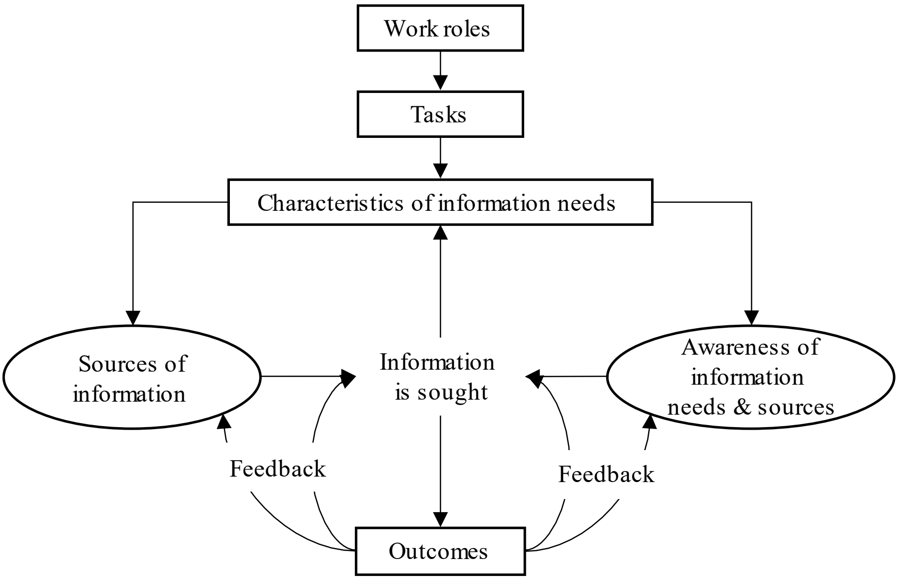

Figure 2-6. Information behavior model for professionals (modified from Leckie, Pettigrew et al. (1996))

The direct significances of investigating risk information behavior are to support risk communication between authority and public, organization design, daily communication between professionals in workplace, instruction design, documentation design, information system design, decision support, interface design. Commercial database and management software for operation management and planning (SAP, Permit to work, Visavi), maintenance management (Fixx, IBM Maximo Application Suite), embedded software for process control, or other digital tools, are already developed for process managers, operators, technicians, etc. There is however incomplete understanding as to whether such services would meet the real-life needs of daily practice. More focused and detailed research into information behavior of professionals who has safety responsibility are sorely needed. The research should have a certain degree of width to cover sufficient decision-makers who have different roles and working contexts.

2.3.6.1 Information needs

Most scholars agree that information seeking arises out of a sense of uncertainty—an anomaly, gap, or problem (Donald 2016). Anomaly here means anomalous state of knowledge (ASK) (Belkin 1980). That is the user's state of knowledge with respect to a topic is in some way inadequate with respect to the person's ability to achieve some goal or to resolve a problematic situation. Thus, there is a need of information. The concept of anomalous state of knowledge addresses the communicative aspect of information science, which is to achieve effective communication of desired information between human generator and human user. Information need is defined as a “function of extrinsic uncertainty produced by a perceived discrepancy between the individual’s current level of certainty about important environmental objects and criterion state one seeks to achieve” (Donald 2016). Attempts to close the perceived discrepancy might later be expressed as a question or action.

In the context of problem-solving, information needs may occur whenever there is a deficiency of the individual knowledge needed for perception, identification, or selection of alternative courses of action. Information need also has a “person-in-situation” feature (Allen 1997). An individual’s knowledge structure affects the interpretation of information need in a problem-solving situation.

However, information need (Savolainen 2012, Savolainen 2017, Cole 2020, Sarkar, Mitsui et al. 2020) is an umbrella term summarizing the motivation. Information need itself is difficult to specify and is unobservable unless information seeking starts. Information need is the primary trigger or driver of information seeking behavior however its nature is determined fundamental triggers and drivers such as the requirements of problem-solving or task performance (Savolainen 2017). For example, conducting risk analysis is an information seeking activity to find out what the risk is for a certain problem-solving or decision-making.

The search for information is a subtask in task performance (Vakkari 2003). When information is considered as a potential response to the need, issues of relevance and quality arise also. However, due to that the fundamental trigger of information need is problem-solving or task performance, the requirements regarding how accurate the information should be, the kind of information that is needed, how much information should be presented, how timely the information should be, search tactics, the relevance and utility judgments towards the information retrieved, should be determined according to the requirements of problem-solving or task performance. In addition to problem-solving, people may want information in the sense of learning or understanding. Some information-related behavior is truly creative in its origins – it is not driven by the need to provide a response to a situation.

There are several classification schemes of information needs. Taylor (1967) classified information needs into four levels: 1) the visceral need: the actual, but unexpressed need for information; 2) the conscious need: the conscious, within-brain description of the need; 3) the formalized need: the formal statement of the need; 4) the compromised need: the question as presented to the information system. Ruthven (2019) analyzed over 1100 posted need statements online and the result show that that the conscious need and formalized needs can be differentiated through linguistic features because the descriptions used are different. In addition to Taylor’s categorization, Weijts, Widdershoven et al. (1993) suggested information needs can be categorized into 1) needs for new information; 2) need to elucidate the information held; 3) need to confirm the information held.

Information needs have been investigated by empirical methods such as task analysis, surveys, interviews, and observations in actual or simulated environment. Information-decision-action task analysis has been used to categorize tasks and to identify associated information needs for drivers (Allen, Lunenfeld et al. 1971). Another approach is to investigate the decision-making process deployed for the tasks of interest (Ward, 2014). In order to know the decision-making process, empirical approaches such as interviews or process monitoring are used first. Sarshar, Haugen et al. (2018) identified risk-related information needed through the planning process by using data gathered from work process descriptions, interviews and workshops with personnel involved in the planning process and structured observations of information flow between meetings. Those methods to assess information needs seem to be universal and have also been applied to bibliographic information systems, management information systems, and command and control systems. The success of these methods is due to that those tasks are well defined in terms of information and control requirements, and investigators are able to identify and interact with users. The empirical methods are restricted by the existence of observable environment, and they are not capable to identify unperceived information needs. Still, the difficulty of measuring information needs should not be ignored as they are psychological internal to people and must be inferred. Empirical methods can obtain only observable approximations. There is a lack of systematic analytical method for the identification of information needs.

Only few studies of risk information needs have been conducted. They are scattered into: public risk communication (Wiedemann, Schütz et al. 1991, Kahlor, Dunwoody et al. 2003, Griffin, Neuwirth et al. 2004, Huurne and Gutteling 2008, Terpstra, Zaalberg et al. 2014), health risk communication, and risk (safety) management within the organization (Beck and Feldman 1983, Nwagwu and Igwe 2015, Sarshar, Haugen et al. 2018), and situation awareness of navigators in maritime operations (Sharma, Nazir et al. 2019).

2.3.6.2 Information seeking

There are two modes of information seeking: surveillance and motivated search. Thus, information acquisition can be opportunistic and intentional. In the surveillance mode, information seekers/decision-makers monitor what is going on and scan their environments for information and solutions (Choudhury and Sampler 1997, Hough and White 2004). Decision-makers may not recognize a “problem” until they have a solution (March 1991). In a motivated search mode, they actively search and gather information that can solve their problems. In either mode, information seeking is a dynamic process as information needs may quickly arise and either be satisfied or fade away. The search process generally stops when a “satisficing solution” has been found (Simon 1997).

Kallehauge (2010) argued for a stage-driven information seeking process from initiation to resolution of work tasks. Figure 2-7 is a model of risk information seeking and processing of patients, proposed by Griffin, Dunwoody et al. (1999). Perceived hazard characteristics, information sufficiency, affective responses towards hazard, anticipatory affective responses towards seeking, social norms, and social trust are the major factors of risk information seeking/avoiding (Choo 2017).

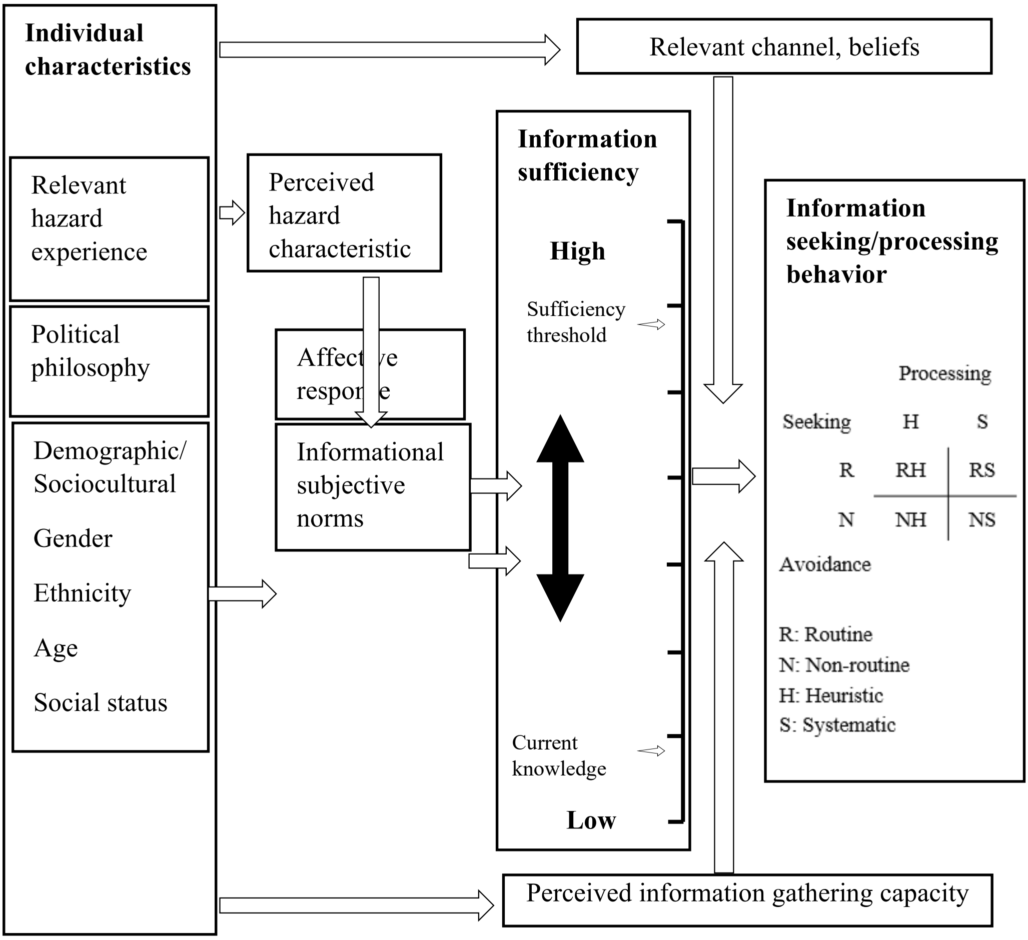

Figure 2-7. Model of patients' risk information seeking and processing (Griffin, Dunwoody et al. 1999). (License for figure reproduction in the thesis is obtained from publisher Elsevier; license number: 5230741049609.)

Several models of the human information seeking process have been proposed, such as by Wilson (1997) and Leckie, Pettigrew et al. (1996). Process-based models characterize the information seeking patterns of information seekers but provide little input in what information people are seeking for. This is because information seeking is dynamic (Huvila 2019), context (Estes 1978), problem (Volkema 1988), and person-specific (O'Reilly 1983). Those generic models of human information seeking behavior needs to be extended in terms of modeling the effects of context and individual differences.

March (1991) criticized that decision-makers and organizations (a) gather information but do not use it, (b) ask for more and ignore it, (c) make decisions first and look for relevant information afterwards, (d) gather and process a great deal of information that has little or no relevance to decisions. As summarid by Rouse and Rouse (1984), psychological experiments found that information seeking is affected by organizational structure, incentive systems, motivation, and group pressures, payoffs and costs, resources available, update rates, amount of information available, diagnosticity of data, distributional characteristics of data and conflicts among sources, individual attention and processing capabilities, biases, information preferences; humans typically are very reluctant to purchase high-cost information despite its high diagnosticity; humans also tend to under and over sample information sources. Those results indicate that humans are not optimal information seekers, especially when they are asked to perform new tasks which has no intrinsic value for them under laboratory environment.

Research about information behavior comes with limitations both due to the problem nature, the participants, and methodological nature. The loose coupling between decision-making activities and an event outcome makes it hard for researchers to use data such as accident reports as reliable indicators of the quality of decision-making activities. A challenging issue is determining the extent to which decision-making activity are faulty. As information behavior is complex, dynamic, personal, and not always observable, the selection of participants, problem presentation, information presentation, the simplification of scenario such as without considering the information access cost etc. may distort the facts. Studies can be complemented using different methods such as high-fidelity simulation or field studies. How to improve the research methods can also be a research topic. In any case, a constrained study can still improve the understanding of information selection and information search of decision-makers in a microworld.

Kolkman, Kok et al. (2005) suggest using mental model mapping as a technique to understand individuals experiences, perceptions, assumptions, knowledge, and subjective beliefs. The individual's interpretation of the problem situation can be clearer when dealing with unstructured problems in complex, multifunction systems. Thus, information seeking, and use can be more structured.

As for information seeking for realistic complex tasks which involve typical levels of ambiguity and tolerance for errors, empirical studies found that experts, such as pilots, are good at searching for and using cues to detect problems and recognize feasible solutions. Empirical study about contextual factors in the context of information search suggests that time pressure increases the amount of information searched for and negatively affects the speed of decision-making (Kerstholt 1996, Khoo and Mosier

2005). Domain knowledge of the decision-maker and task characteristics could impact the information acquisition behavior such as search depth and information types and further task performance (Devine and Kozlowski 1995, Khoo and Mosier 2008). Wild fire incident commanders with higher expertise overall search less information, without affecting the decision quality (Drews, Siebeneck et al. 2015). In addition, incident commanders' information updating during the progression of the scenario involves disproportionately less static information versus dynamic information. For non time-critical decision problems, not the process of information acquisition but the prior knowledge impact the performance. In addition, decision-makers have preferences for one particular approach to information acquisition (Wiggins and Bollwerk 2006).

There are limited studies about information seeking and use for risk-related decision-making activities comparing with their actual populations and varieties. The use and seeking information is so far emphasized in risk-based and risk-informed decision-making. Yanar, Amick et al. (2019) investigated the use of benchmarking information in occupational health and safety decision-making in organizations. Mosier, Bartholomew et al. (2007) focused on the ethical decisions. More studies are conducted to investigate pilots' information behavior and information behavior in emergency responses. Some clues can be obtained from studies in decision-making because decision-making and information behavior are closed tied.

2.3.7 Time to decide for risk-related decision problems

When decision-making is considered as an activity, there are two type of time relevant decision failure modes. The first one is related to timing, the second is related to the duration of the decision-making activity (Hollnagel 2007). Those two types of failure modes are conceptually different. Decision-making can fail because the decision is made at the wrong time (issue of timing), either too early before the necessary information becomes available or too late when the opportunity for action has disappeared. Decision-making can also fail if the decision is made too quickly (issue of duration), that is, because not enough time is spent in finding and considering alternatives, or if too much time is spent in considering the options and alternatives. For example, in emergence where there is little time available, acting on early warning signs, or only considering the first workable solution that come to mind is proper. It may not be proper to save time by making an efficiency-thoroughness trade-off in critical situations. Regardless of whether the decision is made too early or too quickly, the issue behind is that the deficiency of information is not properly resolved.

The fact that time is irreversible makes the set of opportunities to decide shrink overtime. When a decision-maker favors late decision-making, decision is more likely to be made under full information but suboptimal delay; when a decision-maker favors early decision-making, decision is more likely to be made under partial information. The inability to go back in time and decision-maker's bias in the timing to make decisions together can have an effect in both communication mechanism between information holders and decision-makers and decision time (Grenadier, Malenko et al. 2016). Some general perspectives on the role of time in decision-making are discussed by Ariely and Zakay (2001), and Klapproth (2008).

The difficulty is how to determine what timing is a good timing, how long a decision-making duration is proper. At least, an improved perception of time required and time available to resolve the safety critical problem can reduce decision failure (Hogenboom, Parhizkar et al. 2021). The research about features of decision problems and decision-making processes might provide some clues to how long decision-making duration should and could be. Clearly, there are some differences in the duration of each type of decision-making processes, e.g., intuition takes the least time. For threat response, the problem of when to decide (issue of timing) to respond to a threat is resolved by risk monitoring, experience, or regulation rules, in practice. When risk is monitored, a threshold (alarm trip point) is set to trigger a response action (Zio 2018). If risk exceeds the threshold, action should be taken, otherwise not. Hence, the timing to act is when risk exceeds the threshold. For some critical scenarios, especially in emergent situations (evacuation decision), fixed time limits are set by rules.

Many are familiar with the idea that rational decision-making is bounded by decision-maker’s search for all possible solutions. Therefore, the solution chosen is “satisfied” instead of “optimal”. The time to decide is the time when the decision-maker find a satisfactory solution. The criterion of satisfactory is commonly related to resources spent in searching and the potential benefits from solutions. Here, a new proposal is made: The time to decide is bounded by the information available and reachable. As said by Estes (1978): “*Human is slow when he or she is uncertain*”.

Among normative decision theorists, the key is to find the optimal solution for a pre-defined and well-defined decision problem. Subsequently, information about possible solutions is the variable that bounds the timing to decide and the variable one tries to maneuver. Prediction about the future state is a key component to formulate the decision problem; it determines whether there will be a gap and how big the gap is. Information about possible future state is another variable that bounds the timing of decision-making. A hypothesis can be made is that one can analyze the information available for system state prediction to optimize the timing to decide.

2.3.8 Accident prediction by information integration

It is of interest to study accident prediction or prediction of the conditions for accidents. Accident prediction or hazards prediction can provide input for problem detection so that control action can be taken in advance (Klein, Pliske et al. 2005). This prediction also provides time constraints in accident mitigation, up-to-date safety margins for operation and produces information about fault for corrective or predictive measure (Mosier, Sethi et al. 2007).

It is challenging to foresee a major accident during its incubation period (Turner 1978). A severe accident is usually not caused by a single event or a single condition but an effect of interaction of many conditions and events (Saleh, Marais et al. 2010). It would be difficult or impossible to see the outcome when only considering one condition or event due to the indeterminacy of the one condition or event and the limits of knowledge which one knows. Also, it would be difficult or impossible to see all the pre-warnings and interpret them correctly in reality due to ambiguity and fault tolerance. Another challenge is that there are many types of accidents that may happen in a real facility or area, and a large number of scenarios may exist for each type of accident. This potential large number may obfuscate people involved in the situation.

It is necessary to integrate a lot of evidence or inputs to make a prediction, e.g., the prediction of occurrence probability, of an accident of interest. To determine the occurrence probability of a major accident, a capable accident model and available input data are required. A causality model of the major accident is required due to the low sample rates of major accidents and the consequent scarcity of historical accident data (Shmueli 2010). By integrating those input data which might come from disparate domains into an accident model, prediction can be made and supported by empirical data, just like machine learning; machine learning is no more than a collection of algorithms that allow predictions about something that is unknown based on predicators that are known. Every predictor carries information.

Following Turner (1978)'s research, Shaluf, Ahmadun et al. (2002) and Aini and Fakhrul-Razi (2010) have investigated the lengths of the incubation periods of several disasters, although the lengths are arguable due to the inconsistency about start point definition. Still, these studies show that there is enough time to collect and integrate those unnoticed or ignored hazard signals if we know what to monitor and how to monitor the signals.

So far, there have been many attempts in accident prediction or accident diagnosis using operational data, such as Ahn and Park (2009), Haugen, Seljelid et al. (2011), Kim, No et al. (2015), Zhao, Tong et al. (2015), Allalou, Tadjine et al. (2016), El-Gheriani, Khan et al. (2017), Yang and Kim (2020) Montewka, Manderbacka et al. (2022), Cai, Zhang et al. (2021). Effort is also done to integrate organizational, human and technical factors for major accident risk monitoring, such as the "Risk OMT" model (Øien 2001, Vinnem 2010). Methods like hybrid model (combining event tree, fault tree, and Bayesian network (Kjaerulff and L.Madsen 2008)), dynamic Bayesian network, classification algorithms from machine learning (Kuhn and Johnson 2013) (support vector machine, artificial neural network etc.) and risk indexes or influencing factors approach, have been used.

Associated with such attempts, there are some less discussed issues, such as prediction accuracy and its impact, how to use inaccurate (imperfect) prediction if that is the best performance achievable, and the length of the prediction horizon which is about how far ahead the prediction model predicts. In addition, there is a lack of prediction trials on collecting information from multiple actors in the sociotechnical systems for major accident prediction. Actual availability of information is not investigated.

2.3.9 Value of information and prediction

Information does not only have properties such as accuracy, relevance, and availability. Information is also a resource, a commodity (Meadow and Yuan 1997), and there is utility associated with information. The value of information is tied to the decisions which result from the use of the information (Howard 1966). Thus, the value of information is not only related to the information quality but also related to who use it and when it is used.

The Value of Information (VoI) (Howard 1966) is calculated as "the value of the decision situation with the additional information" minus "the value of the current decision situation". In addition, a difference is made between the value of perfect information and value of imperfect information. There are no information gathering/sharing activities that can be more valuable than that quantified by the value of perfect information. The value of information of observing two new evidence is not additive. Instead, it is equivalent to observing one, incorporating it into our current evidence, then observing the other.

As reasoned in Section 2.2.1, risk is a consequence of uncertainty, which can be reduced by gaining information. A hypothesis can be made: the quantification of risk reduction by information can be quantified by the value of information obtained.

Prediction is to provide information about future state and the produced information is used for decision-making. Thus, the value of prediction can be evaluated in the same way as value of information. The prediction value calculation can potentially be used to 1) evaluate the impact of imperfect prediction, 2) and assess the accuracy requirement for accident prediction, 3) optimize time to decide etc.

3 Research gaps, questions, and objectives

3.1 Research gaps

Information can contribute to accident prevention through decision-making. However, the definition, role, and use of information in controlling risk and preventing accidents has not been much discussed. Since this issue is not addressed explicitly, it limits the capability to fully discover the functionality and value from information and brings danger of ignorance and unawareness, and causes misinformation, information over-seeking and over-reliance.

In a sociotechnical system where there are multiple levels of subsystems, the decision problems are diversified and distributed. The way people make decisions varies with their knowledge level, environmental factors, and the type of decision problems. The diversity in decision problems and decision-making processes is likely to influence their information needs. There is a lack of investigation of what types of decision problems exist and of which decision-making processes that decision-makers would like to deploy for their various risk-related decision problems. Since there are different decision-making processes, there is also a lack of investigation of the state of knowledge of the different phases in the various decision-making processes.

Due to the varied decision-making environment and decision problems, the information behavior of the decision-maker should be understood to facilitate better understanding of the information usage to further reduce risk and prevent accidents. When it comes to risk-related roles or scenarios in high-hazardous organizations, there is a lack of research on professionals' information needs, how they seek for information, the use of information, the impact of their information behavior on their task performance, and whether their information environment is sufficient for their tasks.

Since decision-making performance should be evaluated from the process instead of the outcome, it is of interest to investigate the appropriateness of decision-making process including the information behavior. However, there is a lack of investigation of what factors which impact the information behaviors in risk-related decision-making activities.

Information has attributes like quality, availability, information holder etc. There is a lack of investigation of how information attributes impact accident prediction and decision quality of risk-related decisions problems, thus risk and/or accident prevention.

Accident prediction is to provide information to resolve risk-related decision problems. Major accidents rarely occur; thus, it is questionable whether major accident or the preconditions for major accidents can be predicted so that preventive action can be taken in advance. For major accident prediction, there is a lack of major accident prediction trials on collecting and integrating information from multiple actors in the sociotechnical systems.

Understandably, the prediction of major accidents will be imperfect; however, there is a lack of research about how the imperfect prediction impacts risk-related decision-making activity. A corresponding problem is how to assess the accuracy requirement for accident prediction.

It is unclear what kind of accident prevention measures can be further developed from the information-based strategy. So far, hazard detection and monitoring, accident prognosis and prediction (such as earthquake, hurricane, nuclear core damage) have been applied in practice. A comprehensive and systematic explanation of why information contribute to accident prevention perhaps can facilitate more measures or more effective measures for accident prevention. In addition, the question of to what extent that those measures could contribute to major accident prevention or simply reduce undesired consequences remains unanswered.

Further, it can be worth to address 1) the cost, feasibility, and effectiveness for measure implementation, comparing with existing accident prevention strategies such as level of protection (CCPS 2011), barrier(Sklet 2006, Liu 2020) concept ; 2) whether risk can be further reduced if combining information-based strategies with the level of protection and barrier concept. According to the ALARP (as low as reasonably practical) principle, risk should be reduced to reasonably practical level. Acceptable risk level is also subject to the cost and effectiveness of risk control measures. The acceptable risk level can become lower and therefore the safety level will be increased if the cost for risk reduction is decreased or the measure effectiveness is improved by implementing the information-based strategies. To address the feasibility, effectiveness and cost, a way to model and evaluate the strategy needs to be established as well.

Overall, these research gaps prevent the effective usage of information for risk control and accident prevention.

3.2 Research questions

Based on the research rationale and overall research aim, the overarching research question is framed as:

> How can risk information effectively contribute to major accident prevention through decision-making in sociotechnical systems with a focus on maritime industry?

The overarching research question is decomposed into 5 sub research questions. The 1st question addresses the information requirements for risk-related decision-making activities. The 2nd question scrutinizes the environment factors that may impact the performance of risk-related decision-making activity. The 3rd question is about the features of decision problems that can be used to support decision-making process prediction and information requirement prediction. The 4th question concerns accident prediction where different information is fused to provide a signal about accident occurrence so that decision-making activity can be initiated. The 5th question deals with optimal response time for threat handling which can be constrained by the available information. The relation between these questions is illustrated by Figure 1-2.

Major groups of decision-making processes have been proposed from the scholars in the field of psychology and decision science. There are little discussions and comparisons of the information needs between different decision-making processes. The 1st research question is formulated:

Research question 1: What information is needed for risk-related decision-making activities and specifically what types can be called risk information among all the information requirements?

Decision-making activity including decision-makers' information behavior is constrained by the environment or context factors. It is beneficial to have an overview of the context factors which impact the human decision-making performance especially the information acquisition, processing, and utilization. The 2nd question is formulated as:

Research question 2: What context factors impact human decision-making performance especially in information retrieving and processing?

Major accidents are results of many unclosed gaps. Those gaps are diversified not only in terms of what the gaps are, but also in their features. Understanding their features can perhaps contribute to solving the gaps in a proper way so that such accidents can be prevented more effectively, and safety can be assured. The 3rd question is formulated as:

Research question 3: If information needs vary and are dependent on decision-making process, is there a way to predict decision-making process through decision analysis?

For major accident prediction, there is a lack of prediction trials on collecting information from multiple actors in the sociotechnical systems. The 4th research question is formulated as:

Research question 4: Can major accidents be predicted by accumulating information and reducing uncertainty?

One type of decision problems for accident prevention is threat response. Timing of decision impacts effect of response action and risk. It is challenging to achieve perfect prediction due to complexity of system behavior, randomness, and scarcity of major accidents. When imperfect prediction is used as input for threat response decision problems, the accuracy (including specification and sensitivity) of prediction impacts decision-making. However, the prediction accuracy is dependent on information availability. Thus, it can be possible to obtain an optimal response time point from the perspective of information availability. Research question 5 is formulated as:

Research question 5: How is the optimal decision time for threat response decision problems bounded by information availability?

3.3 Research objectives

The general objective of this thesis is to provide new knowledge and a new perspective for utilizing information more effectively in decision-making for major accident prevention in sociotechnical systems. From the research questions, corresponding sub objectives have been formulated.

The subobjectives include:

Subobjective 1: Provide a list of categorized information that is needed for risk-related decision-making activities from the perspective of varied decision-making processes.

Subobjective 2: Give an overview of relevant factors that might impact operator's decision-making process with a focus on highly autonomous ships where less, but crucial decisions need to be made by human operators.

Subobjective 3: Develop a method to analyze decision problems to provide insight in decision-making process prediction.

Subobjective 4: Verify the hypothesis that major accidents can be predicted if we can accumulate information from different sources and integrate them into a well-developed accident model? by case study of a well investigated major accident.

Subobjective 5: Develop a method that can be used to calculate the optimal decision time, so that risk can be minimized further from the perspective of prediction accuracy and information availability.

3.4 Definition clarification and establishment

For a clear description of the research work, the definitions of terms should be clear. In this PhD work, some terms need to be established to form a clear research topic, while some terms can be general but with different meanings under different contexts. Therefore, clarification is necessary. This section provides a discussion and clarification of those important terms used in the thesis to avoid confusion and misunderstanding.

3.4.1 Information and knowledge

In this thesis, one of the central themes is information. There have been discussions about what is information. In this thesis, the definition from Zins (2007) is adopted, that information is “the facts and ideas that are available to be known by somebody at a given moment in time”. Information can be (i) universal, existing as symbols and signs; (ii) subjective, the meaning to which symbols attach; or (iii) both. The main characteristics of information are accuracy, relevance, completeness, and availability. Information is presented within context so that it is relevant and useful to the person who wants it and can be used in the process of decision-making. It can be communicated in the form of a message or through observation and can be obtained from various sources such as books, guidelines, colleagues, websites, sensors, information systems, etc.

The definition of knowledge used in this thesis is “a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information” (Davenport and Prusak 1998). Therefore, knowledge is internal to a person while information is external and in principle can be available to anyone. However, the value of information will depend on a person’s knowledge. Presenting the same information to two decision-makers doesn’t guarantee the same outcome due to their different prior knowledge. Knowledge will determine what information is relevant and how it is to be used. Knowledge will also impact what decision-making process would be used for a certain decision problem. At the same time, new knowledge can be created after taking in information from the external environment.

In this thesis, due to the focus on macro cognitive instead of micro cognitive aspects of decision-making, judgement in a further detailed level is not considered because the authors do not have neuroscience background. Thus, the authors assume that if two decision-makers have completely the same knowledge and with access to the same information under the same environment condition, their decision output for the same decision problem will be the same.

3.4.2 Uncertainty

The generic definition of uncertainty is “a state of incomplete knowledge” or “a state of mind” in perception of an object (Aven, Ben-Haim et al. 2018). Uncertainty is used in “the situation which involves imperfect and/or unknown information”. It applies to predictions of future events, to physical measurements that are already made, or to the unknown. Uncertainty arises in partially observable and/or stochastic environments, as well as due to ignorance and/or indolence”.

The term “uncertainty” is used on many occasions in the thesis and the attached articles. The term uncertainty has the same meaning but varies in “the knowledge of who” and the type of "object". The type of objects relevant here are "event", "real world environment", "past", "future state of the system under consideration", "decision problem", "impact of solution on the system". Knowledge owner relevant here are "the knowledge of the world (humankind)", "the knowledge of the decision maker", "the accumulated knowledge from all realistically accessible information sources" etc.

In the case of accident prediction, the object is "future state of the system under consideration", which is to be predicted; the knowledge owner is the one who make the prediction. In the case of decision problem, the object is all elements in the problem space. The knowledge owner is the decision maker. In the case of decision impact, the knowledge owner can be either the stake holders or the decision maker.

In section 2.2.1, where ISO 31000 risk management (ISO 31 000 2009) is referred, the uncertainty definition used in the standard is used, i.e., *"uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood"*. In this definition, it is implicit in term of "who's knowledge" which may imply "decision makers or risk analyst or knowledge of the world".

3.4.3 Decision-making

In this thesis, the term decision-making means the activity to solve a decision problem. A decision-making activity follows a general problem-solving process from problem detection to a solution chosen (Brim 1962, Mintzberg, Raisinghani et al. 1976, Hansson 2005) as shown by Figure 3-1. Thus, the term decision-making is equivalent to problem-solving in this thesis.

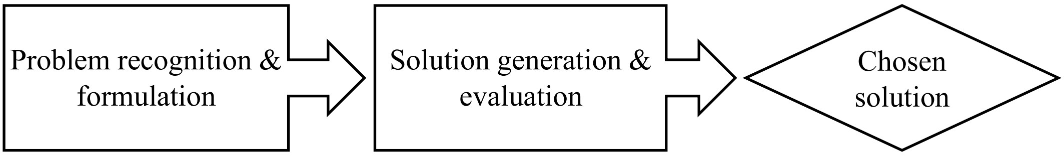

Figure 3-1. Generic decision-making process from problem recognition to solution

While in many other literatures, the term decision-making means the "evaluating and choosing among alternative actions (options, alternatives)" in response to a defined decision problem. The phase of defining a decision problem is excluded in those literatures, as Simon, Dantzig et al. (1987) wrote:

> *"The work of managers, of scientists, of engineers, of lawyers -- the work that steers the course of society and its economic and governmental organizations -- is largely work of making decisions and solving problems. It is work of choosing issues that require attention, setting goals, finding or designing suitable courses of action, and evaluating and choosing among alternative actions. The first three of these activities -- fixing agendas, setting goals, and*

> *designing actions -- are usually called problem solving; the last, evaluating and choosing, is usually called decision making."*

However, the separation between problem-solving and decision-making becomes less necessary when talking about how decisions are made or how an action is determined in daily life. The rationales to synchronize decision-making and problem-solving are:

- For decision-making in daily life, there is less about evaluating and choosing but more about copying a workable solution (Klein 1993). Evaluating and choosing part can be skipped.
- For decision-making in daily life, there is more than evaluating and choosing. Decision-making also includes the part of define the decision problem and finding solution and deciding one. Setting goals, finding suitable course of action are necessary steps to ensure quality of the chosen solution (Klein 1993).

When decision-making is considered the same as problem-solving, the next question is what a "decision problem" should be defined as. In other words, what is the definition of "problem"? There are three commonly used definition of "problem": "gap", "realistic opportunities for improvement" and "solution".

The "gap" definition is favored to address the initiation of decision-making or problem solving (Cowan 1986) and goal-oriented behavior of human action (Frensch and Funke 1995). The "realistic opportunities for improvement" definition is favored in the case that "a problem is a problem because there is potential for improvement and the improvement potential is feasible (Hoppe 2017). It emphasizes the direction of action (to improve) and the feasibility (realism). A gap can exist before realistic opportunities show up. The "solution" definition is favored in the argument that a problem is eventually settled by the solution taken in the end and people may not even realize there is a problem before a solution pops up (March 1991).

3.4.4 Decision problem, decision[2], and option (alternatives)

In this thesis, the gap-based problem definition is taken, because it fits well to the goal for a better decision-making process and the formulation of risk-related decision problem.

A decision problem is seen as a gap between the true state and the desired state, e.g., a deviation from norm, standard, or objectives. Concerning all relevant decision-makers who are the controllers of risk, their problems are defined as the gap between their production objectives, safety objectives and other objectives, and the actual state of the

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[2] Note: In article 3, decision and decision problem have the same meaning, which is a gap between the true state and the desired state.

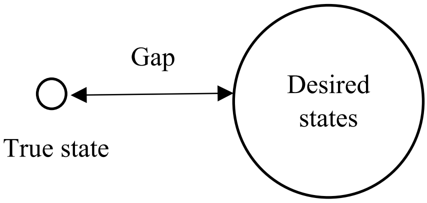

Figure 3-2. Illustration of problem definition (from article 1)

system. Figure 3-2 illustrates the gap definition. In the figure, the size of the circle is used to indicate the number of states. The true state is represented by the small circle, while desired future states are represented by the large circle. The true state becomes regarded as safe if it is moved into the confines of desired states, i.e., the gap is closed.

Decision means the chosen solution for a decision problem. Therefore, a decision is an output from an decision-making activity. Throughout this thesis, more focus is put on decision problems that should be detected and solved properly through decision-making activities to which information is an input.

3.4.5 Risk-related decision problems[3]

Following the gap-based definition of decision problems, a risk-related decision problem is considered to exist when 1) the potential state of the system of interest is likely to be outside the desired safe state (a state with acceptable risk), or 2) an action to achieve other objectives or system functions will potentially move the system state outside the required safety boundary. The existence of such a gap would threaten the safety of the system if the problem does not get well-resolved. Therefore, we define risk-related decision problems as decision problems where the outcome will possibly influence the major accident risk for a sociotechnical system, either by decreasing or increasing the risk. An impact can be made because the chosen solution introduces hazards, releases hazards, influences the function of barriers, impacts the occurrence probability of undesired events or mitigation of undesired consequences, etc. Included in the definition are also decision problems which impact risk "indirectly", such as decision problems on maintenance budgets for safety equipment, manning levels for positions that manage and/or control risk, inspection, maintenance planning, etc.

3.4.6 Features and dimensions

A multi-dimensional approach could be developed and used to analyze risk-related decision problems to obtain a better understanding of the features of these decisions. An improved understanding of the decision problem can in turn form the basis for tailoring the information needed to make these types of decisions. Before being able to propose and define the dimensions, we need to define what feature and dimension means. In this thesis, a problem feature is defined as a specific attribute of a decision

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[3] Note: The term risk-related decision instead of risk-related decision problem is used in article 3.

problem; while a dimension represents a distinct perspective and includes a set of problem features. For instance, whether the problem is simple or complicated is a feature of the problem in a “complicatedness” dimension. Likewise, whether the problem is critical or non-critical is a feature of the problem in a “criticality” dimension.

3.4.7 Time point of response, response time, and response

For the decision-making of risk-related decision problems, we do not only need to determine what to do but may also have to determine when to decide to handle a hazardous situation. In the thesis, it is proposed that “when to decide” is constrained by information and can be determined by the value of information. For the further development of the mathematical solution, the meaning of terms “response”, “time point of response” and “response time” are defined. A response is a decision-making activity which includes making a prediction and initiating an action based on the predicted result. The action will be implemented if the prediction model predicts “accident”, though not implemented if the model predicts “no accident”. As illustrated by Figure 3-3, the response time t_r is a time interval and it is defined in relation to time t_t when the hazardous situation terminates; the time point of response t_{pr} is the time point to make & accept a prediction and implement the corresponding response action. Prediction horizon hereby means how far into the future that the prediction model predicts the outcomes.

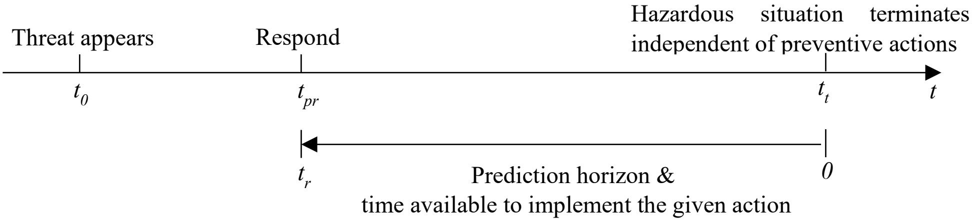

Figure 3-3. Response time where the time is not represented to scale (modified from article 5)

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4 Research approach

The PhD research project consists of 3 types of activities: course work, main research work to explore and address the research questions and summarization of the work into the PhD thesis. Course work and research have been performed concurrently. Summarization of all the work is done at the end of the PhD.

The overall research process is described in section 4.1. Generic research methods which have been used to meet the overall research objectives are described in section 4.2. Detailed research processes to reach sub objectives are described in section 4.3. The generic research methods include literature study to obtain solid knowledge about resolved and unresolved issues, scientific inquiry, discourse, exploration, reasoning and elaborations of concepts, case study for verification and demonstration, deduction through mathematics to form a rigid reasoning and conclusion.

4.1 Overall research process

The research work done within the PhD period is mainly conceptual, theoretical, analytical, exploratory. The research work is also multidisciplinary, and it has involved several branches surrounding the central goal, which is to build up a concept of information-based accident prevention strategies.

The overall research process of the PhD work is illustrated by Figure 4-1. The overall research question was decomposed into 5 sub research questions and 5 subobjectives correspondingly. The summarized outputs from reaching 5 subobjectives answer the main research questions and achieve the overall aim.

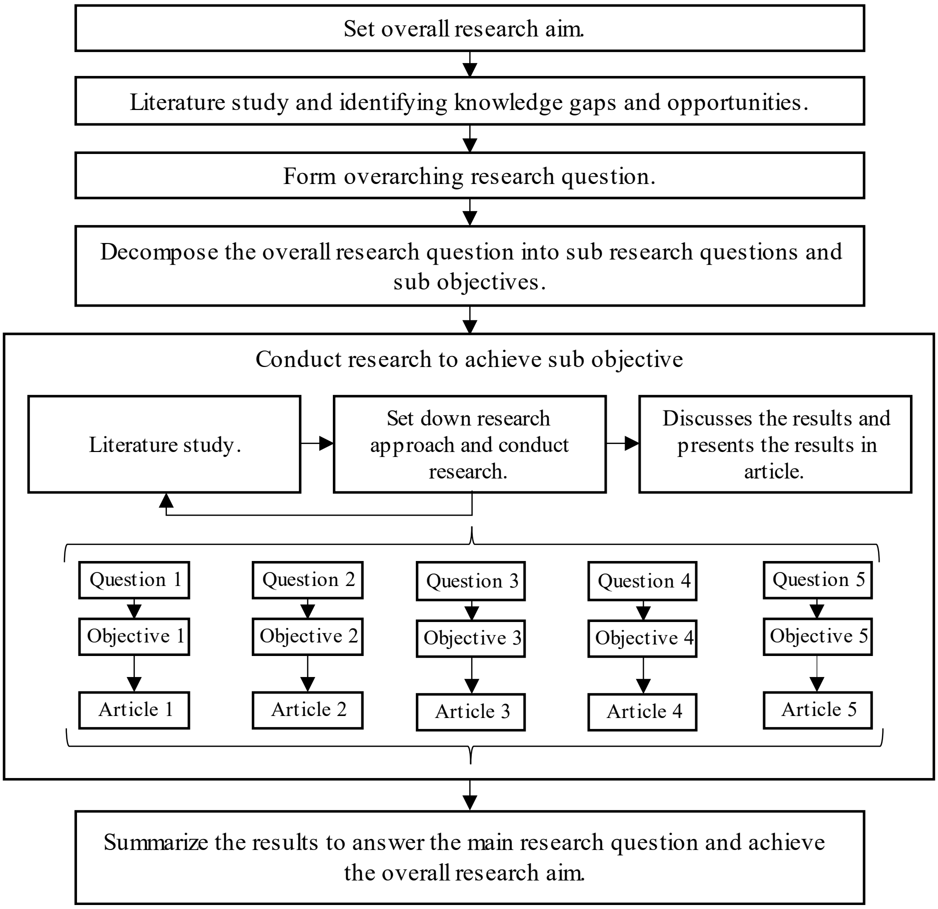


Figure 4-1. Illustration of the overall research process

4.2 Generic methods applied in the PhD research

4.2.1 Literature study

Literature study is commonly used in research. Literature study is an ongoing activity with the research work and used in every corner to 1) gain knowledge about research status of a specific topic, 2) form research ideas, 3) generate new knowledge, 4) provide evidence or arguments relevant to the questions addressed in the articles, 5) know the proposed definitions of terms, 6) fetch values of variables, 7) learn about research methods, etc.

Online databases such as Google scholar and Web of Science, and relevant scientific journals such as *Safety Science*, *Journal of Loss Prevention in the Process Industries* have been used the most to search for relevant books, reports and/or articles. University library and Oria are the ones used the most to access physical or digital contents.

4.2.2 Scientific inquiry

Research starts with a triggering question, a wonder of what, why, or how, even though the final work may not answer the original question. One question raised in the very beginning addresses a “minesweeper problem”. The question starts with the phenomenon description: “If there is a hidden bomb in a football field. There is high uncertainty about the bomb location because the bomb can be any place. One strategy to find the bomb is to search and clear area by area. The more areas that are cleared, the larger the probability that the bomb will be in the remaining areas which means the uncertainty of the bomb location is reduced”. The emerged questions are: “Why this strategy works?”; “under what condition does it not work?”; “how could we explain this uncertainty reduction phenomena?”; and “how can we apply it to accident prevention?”. Those questions triggered an idea of an information-based strategy and some subsequent questions related to it.

Another type of questions like “What is the meaning of doing this research work?”; “what can we achieve by finding this out, by proposing this approach, by solving this problem?” are also thought provoking, even though research work itself is meaningful regardless of whether it can change the world or not. Those questions pushed researchers to think whether the research work is carried out on the right track; whether the current research work is trying to solve the original question and the relation between the question addressed now and the original question. Questions like “Are the research methods solid enough?” were also raised commonly to understand the limitations and boundaries of the obtained results.

4.2.3 Exploration

To answer the triggering question, exploration is the first step, both to satisfy my curiosity about the subject or sub-subject and to understand the phenomenon. Understanding the phenomenon is crucial to know the reasonable questions to ask, the subsequent studies to conduct, the feasibility and methods of conducting more extensive studies. Exploration usually ends with a talk with experts but includes searching online and literatures studies. Since the PhD work researched several branches from the central topic, there is an exploration phase for each branch topic also. For example, quite a lot of explorations were done in determining what are the proper research questions to address when studying accident prediction and information needs.

4.2.4 Scientific discourse

Scientific discourse is an activity to discuss, debate, scrutinize, reflect with scientific peers, including convince or persuade, with careful reasoning and argumentation through a homogenous and closed communication. There are many discourse activities during the whole PhD process, including the many discussions and argumentations between me and my supervisors, two conference presentations, communication with editors and anonymous reviewers during the publication processes, presentations in the internal seminars, discussions with colleagues. Those scientific discourses have also influenced my work.

4.2.5 Elaborated reasoning

Reasoning is the process which uses existing knowledge to draw conclusion, make predictions, or construct explanations. Reasoning activities can be called “thought experiments” which involve creative imagination and visualization. New knowledge or insight can be acquired by reasoning. The brain is a main tool for this PhD research. Reasoning and thinking are undeniable used frequently as research cannot be done without thinking, even if an induction or deduction process might not be strictly followed as an overall research approach for any article as may be seen in many other explanatory research papers.

4.2.6 Case studies

A case study is a detailed examination of a particular case and thus has a very narrow focus. A case study provides detailed descriptive data which is unique to the case(s) studied but potentially can provide an understanding of a larger class of similar units and even challenge existing theories and practices. Major accidents do not happen frequently and usually do not repeat themselves as replicas. Thus, case study is a common method used in research about major accidents. Within the PhD research work, case study as a research method is used four times for verification and/or demonstration.

The first case study is about major accident prediction. The capsizing of the Korea RORO passenger ferry MV Sewol is used as the case to demonstrate that accident can potentially be predicted if relevant information from different information holders is collected and integrated into a capsizing model.

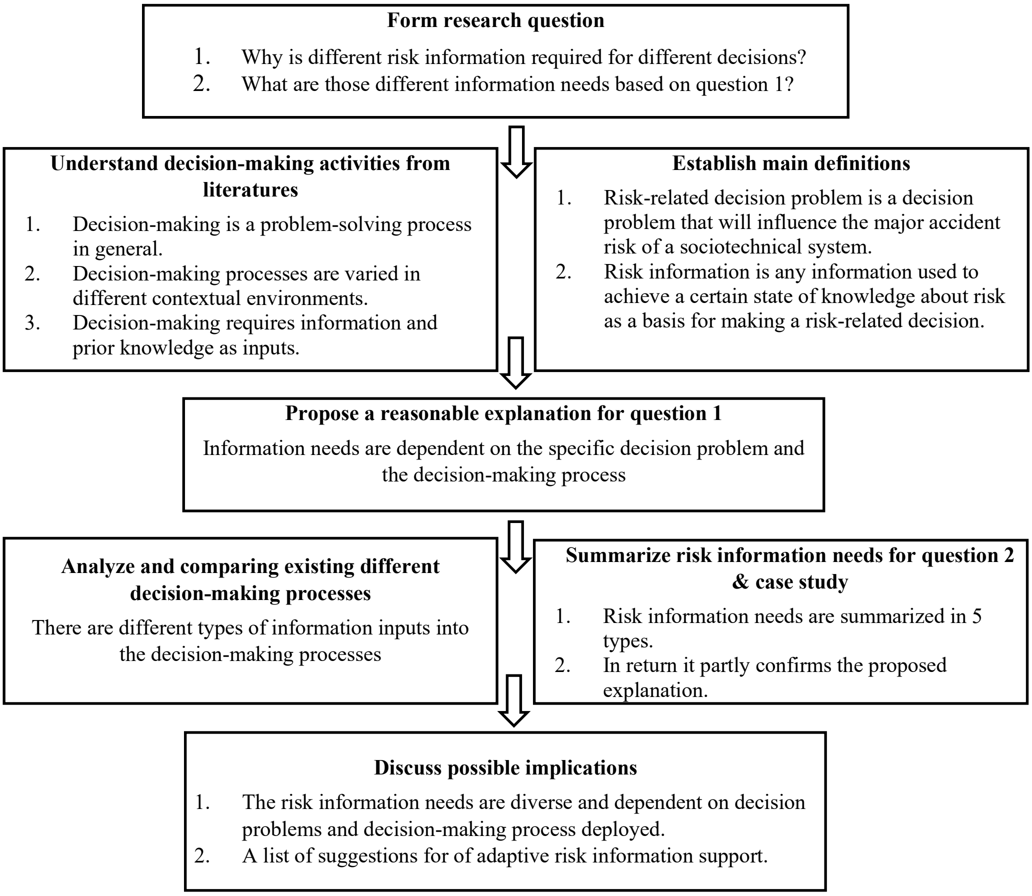
The second case study is to illustrate the differences in information needs following different decision-making processes. The basic scenario used in the case study is the handling of iceberg-FPSO (Floating Production Storage and Offloading unit) collision case. The responding problem to iceberg threat is used again as an example to illustrate the application of the proposed multi-dimensional decision problem characterization approach.

In the last article, the iceberg collision scenario is still used but with a focus on response timing which is bounded by the information and collision prediction reliability. Iceberg collision is a good case for study because iceberg drifting is observable so that collision is not purely stochastic but partially predictable. Both ferry capsizing and iceberg-FPSO collision meet the criteria of major accident because it is a type of rare events in terms of likelihood but high severity in terms of consequences.

4.3 Specific method(s) and process for each subobjective

4.3.1 Research process for subobjective 1

The objective for research question 1 is to identify information needs for risk-related decisions, considering varied decision-making processes and decision problems. A qualitative research approach is taken to achieve the research objective. The research process is shown in Figure 4-2, where bold texts highlight the research activities, and the non-bolded texts are the main outputs from the research activities.



Form research question

1. Why is different risk information required for different decisions?
2. What are those different information needs based on question 1?

Understand decision-making activities from literatures

1. Decision-making is a problem-solving process in general.
2. Decision-making processes are varied in different contextual environments.
3. Decision-making requires information and prior knowledge as inputs.

Establish main definitions

1. Risk-related decision problem is a decision problem that will influence the major accident risk of a sociotechnical system.
2. Risk information is any information used to achieve a certain state of knowledge about risk as a basis for making a risk-related decision.

Propose a reasonable explanation for question 1

Information needs are dependent on the specific decision problem and the decision-making process

Analyze and comparing existing different decision-making processes

There are different types of information inputs into the decision-making processes

Summarize risk information needs for question 2 & case study

1. Risk information needs are summarized in 5 types.
2. In return it partly confirms the proposed explanation.

Discuss possible implications

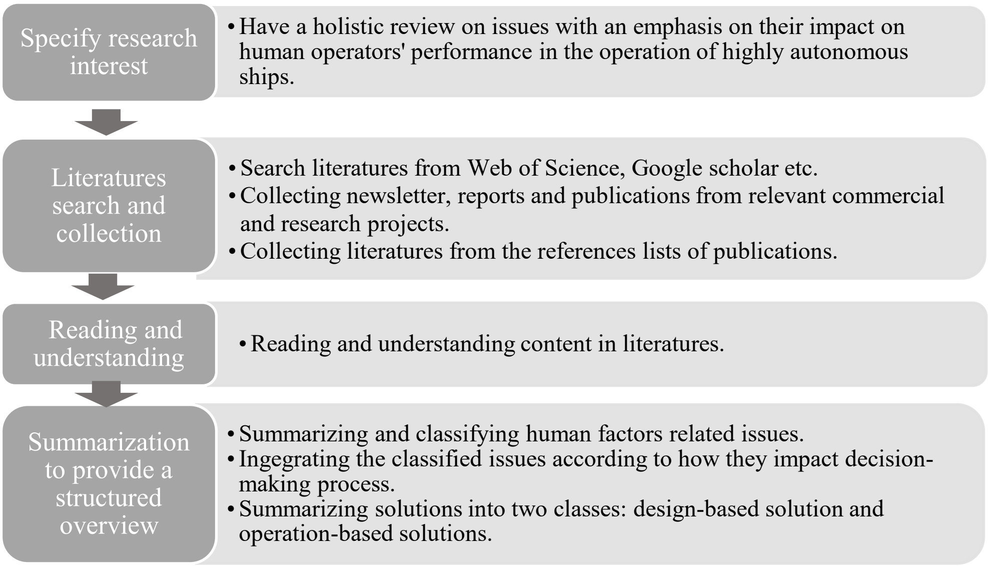
1. The risk information needs are diverse and dependent on decision problems and decision-making process deployed.
2. A list of suggestions for of adaptive risk information support.

Figure 4-2. Research process for question 1

The reasons to choose a qualitative research approach are: 1) The research is explorative because there is no mature practice yet; 2) the existing research conducted are mostly descriptive; 3) there is lack of practices and procedures to establish a quantitative analysis. Even though information needs are dependent on the specific decision problem and the decision-making process, the further analysis is only done by examining and comparing decision-making processes because of the high diversity of decision problems but limited types of decision-making process. Further research can be conducted by comparing the information needs from the perspective of risk-related decision problems.

4.3.2 Research process for subobjective 2

The research objective of question 2 is to provide an overview of challenges and possible solutions for the human performance in the operation of highly autonomous ships. Literature review is a common approach to provide an overview of a certain subject. In addition, highly autonomous ships are still under developing, thus, studies or surveys, investigations on real ship operation are not feasible. Thus, the research methods used are literature review and classification. The research process is illustrated by Figure 4-3. Human factor challenges are classified into 10 categories based on the knowledge provided from literatures. Factors are investigated from their impacts on the different phases of decision-making process: 1) problem recognition, 2) decision-making, 3) action implementation. Possible solutions are summarized from two classes: design-based solutions and operation-based solutions.



Specify research interest

- Have a holistic review on issues with an emphasis on their impact on human operators' performance in the operation of highly autonomous ships.

Literatures search and collection

- Search literatures from Web of Science, Google scholar etc.
- Collecting newsletter, reports and publications from relevant commercial and research projects.
- Collecting literatures from the references lists of publications.

Reading and understanding

- Reading and understanding content in literatures.

Summarization to provide a structured overview

- Summarizing and classifying human factors related issues.
- Ingegrating the classified issues according to how they impact decision-making process.
- Summarizing solutions into two classes: design-based solution and operation-based solutions.

Figure 4-3. Research process for question 2

For far, there is limited research on human performance in the operation of highly autonomous ships. The quantity of literatures is not massive. Literatures addressing human performance when cooperating with automated functions onboard were also included. Existing literatures can be classified into 3 groups. The first group is studies about human cooperating with highly autonomous ships or highly automated functions onboard. In addition to publications from academia, there have been several pioneer projects about autonomous and/or remotely operated ships, where human reliability or human factors were concerned. Reports and newsletter from those projects are also used as information sources. The second group is literatures about human machine cooperation, and human decision-making behavior in a complex, dynamic environment. The third group is studies from other industries such as space, aviation, automotive, process where high level of automated functions has been implemented.

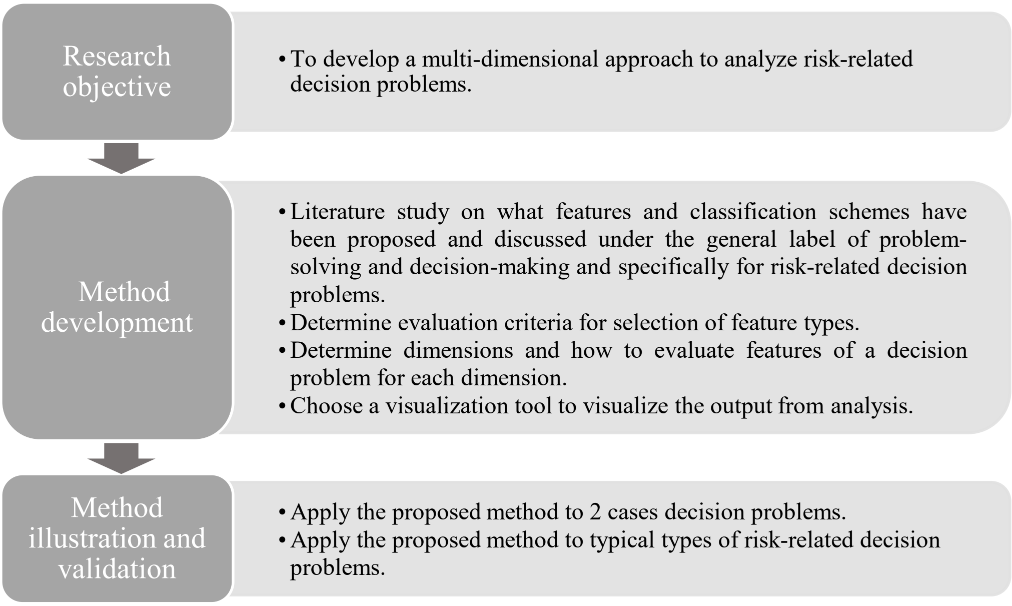
This research is to provide an overview. The quality of overview is limited by the 1) coverage of literatures, 2) quality of literatures, 3) validation of the knowledge from those literatures in future.

4.3.3 Research process for subobjective 3

The research objective of question 3 is to develop a multi-dimensional characterization approach to analyze risk-related decision problems with a purpose of providing insight in decision-making process and information needs prediction. A decision analysis method development approach is taken to achieve the research objective. The research process is illustrated by Figure 4-4.

The research starts with understanding what kinds of features and classification schemes have been proposed and discussed under the label of problem-solving and decision-making in general and specifically for risk-related decision problems. A literature study was conducted to have an overview. The literatures covered come from multiple disciplines psychology, cognitive sciences, system science and engineering are covered. Further, to fit in the purpose of providing indications in decision-making process prediction, two evaluation criteria is proposed to determine what types of features should be included. Afterwards, dimensions and how to evaluate the feature of a decision problem for each dimension are proposed based on the results from literature study and evaluation criteria through elaborated reasoning. Two decision-problems cases are analyzed by the proposed multi-dimensional characterization methods for illustration and validation. Typical risk-related decision problems are analyzed by the proposed dimensions to see whether the proposed multi-dimensional approach gives reasonable results.

The limitation of the research method applied comes from method validation part. The sizes of cases used from method validation is limited. In addition, the proposed multi-dimensional approach is qualitative, and the feature evaluation can be subjective which may impact the validation results. More cases should be used to validate the approach and exam the applicability of the proposed approach.



- To develop a multi-dimensional approach to analyze risk-related decision problems.

- Literature study on what features and classification schemes have been proposed and discussed under the general label of problem-solving and decision-making and specifically for risk-related decision problems.
- Determine evaluation criteria for selection of feature types.
- Determine dimensions and how to evaluate features of a decision problem for each dimension.
- Choose a visualization tool to visualize the output from analysis.

- Apply the proposed method to 2 cases decision problems.
- Apply the proposed method to typical types of risk-related decision problems.

Figure 4-4. Research process for question 3

4.3.4 Research process for subobjective 4

The research objective is to verify the hypothesis that major accidents can be predicted if we can accumulate information from different sources and integrate them into a well-developed accident model. The focus of this research is on the investigation of availability of information from multiple information holders with time prior to the occurrence of the accident. The pre-warnings and their availability in time was identified and integrated through an accident prediction model to demonstrate if there were enough pre-warnings to provide prediction about the occurrence of the capsizing accident. The research process is presented by Figure 4-5.

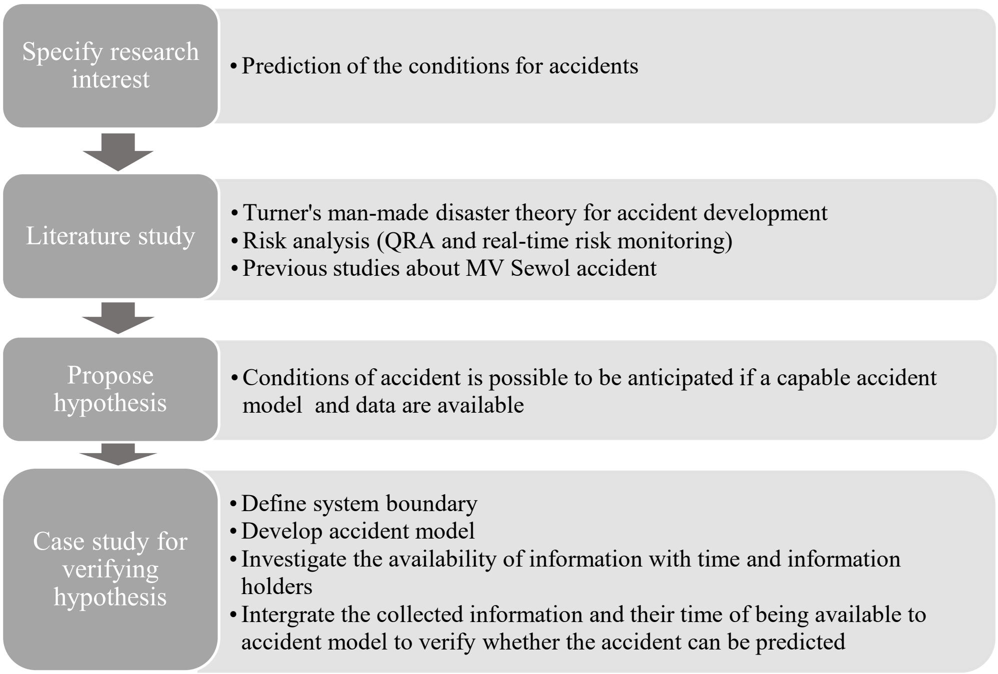


Figure 4-5. Research process for question 4

Due to the dynamic and complexity feature of sociotechnical system which increase the difficulty and time requirement for the study, try-out research is conducted on one specific accident instead of taking a statistic approach with a large sample size. The chosen accident is a capsizing accident with a fatality of 304 people. The consequence of the accident is severe; thus, it falls into the category of major accidents. This accident is well studied which means that the extent of false or incomplete information is lower comparing with accident cases which are not intensively analyzed.

To accommodate the complexity of accident causation for socio-technical system, which involved multiple hierarchical levels of actors, the capsizing accident model was developed based on the accident causation model for sociotechnical system proposed by Rasmussen (1997). The accident model is presented in a form of Bayesian network, which is a type of influence diagrams, for its capability to illustrate and reason through the cause-effect chain (Kjaerulff and L.Madsen 2008). An accident model based on Bayesian network can also be used for probabilistic prediction by information integration.

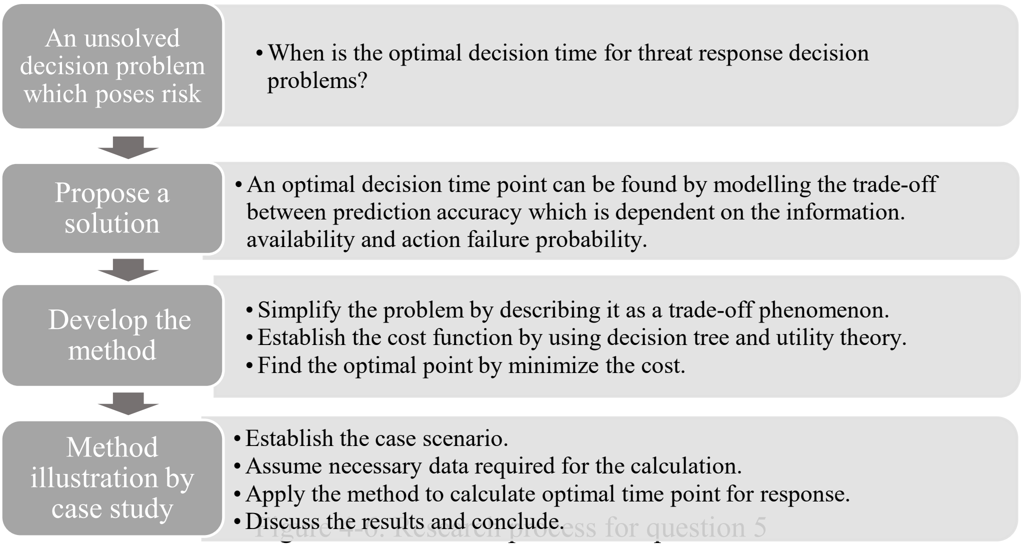
When it comes to data collection, two routes were followed. One is driven by the accident model. Herein, following each node in the Bayesian network accident model to identify: 1) Condition of the node, 2) who could be the information holder, 2) whether the node condition was known by the information holder, and 3) when the information became available. The second route is driven by the available information sources.

Herein, the main information sources were searched to seek data about information availability, information holders and its time of being available. Data was collected from new articles, videos, court records, accident investigation report, and scientific papers which analyze the capsizing accident. The data might still be biased and incomplete.

Unavoidably, the analysis was affected by hindsight bias because data collection and study are done after the accident. Theoretically, pre-accident data and prediction from accident model should be used to verify the prediction possibility. However, such approach is time consuming and resource consuming when it comes to case monitoring and data recording. Difficulties arise from the long-time span of accident incubation period, involvement of multiple levels of actors and rarity of capsizing accident of the same type. Conditions for taking such approach did not exist when this research work was initiated.

4.3.5 Research process for subobjective 5

The research objective for question 5 is to develop a method that can be used to calculate the optimal decision time for threat response decision problems so that risk can be minimized. Quantitative solution is preferred when possible. Such is the reason why a mathematical modelling is chosen as the research method. Mathematical modelling is an important tool for engineering analysis even though the solution obtained through the model is an approximation, because the real situation is often very complex. To obtain the optimal response time, a mathematical model is developed to describe the problem by a set of variables and a set of equations that establish relationships between the variables. Optimal response time is calculated through solving the equations. The developed model can also be used for further inference, such as calculating the prediction accuracy requirements. Figure 4-6 presents the research process.



An unsolved decision problem which poses risk

- When is the optimal decision time for threat response decision problems?

Propose a solution

- An optimal decision time point can be found by modelling the trade-off between prediction accuracy which is dependent on the information. availability and action failure probability.

Develop the method

- Simplify the problem by describing it as a trade-off phenomenon.
- Establish the cost function by using decision tree and utility theory.
- Find the optimal point by minimize the cost.

Method illustration by case study

- Establish the case scenario.
- Assume necessary data required for the calculation.
- Apply the method to calculate optimal time point for response.
- Discuss the results and conclude.

Figure 4-6. Research process for question 5

The mathematical model is a cost function developed from a decision tree (Kamiński, Jakubczyk et al. 2018) analysis of possible scenarios. A decision tree is a decision support tool that uses a tree-like model of decisions and their possible consequences, including chance event outcomes, resource costs, and utility. It is a way to display conditional control statements and can be used as a descriptive means for calculating conditional probabilities. Utility function can be easily developed after a decision tree is created. Utility theory is the classical theory to develop cost function and optimization, thus it is used in the proposed solution.

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5 Results and discussions

This section summarizes the main results and contributions from the attempt to achieve the defined 5 subobjectives. 5 articles are produced during the PhD period as a result. Figure 5-1 gives an overview of the 5 articles. Further details of the results are presented in each article in Part II. Each article addresses a sub question that is relevant to information-based strategies. Article 1 studied the information needs in making risk-related decisions. Article 2 reviewed factors that impact human decision-making activities during the operation of highly autonomous ships. Following Article 1, Article 3 proposed a dimensional approach to analyze risk-related decision problems to facilitate proper problem specific decision-making process and further investigation of information need. Article 4 addressed accident prediction by information accumulation and integration. Article 5 proposed a mathematical model to calculate the response time for threat handling which is bounded by potential information available. The main results and discussions are outlined in the following sections.

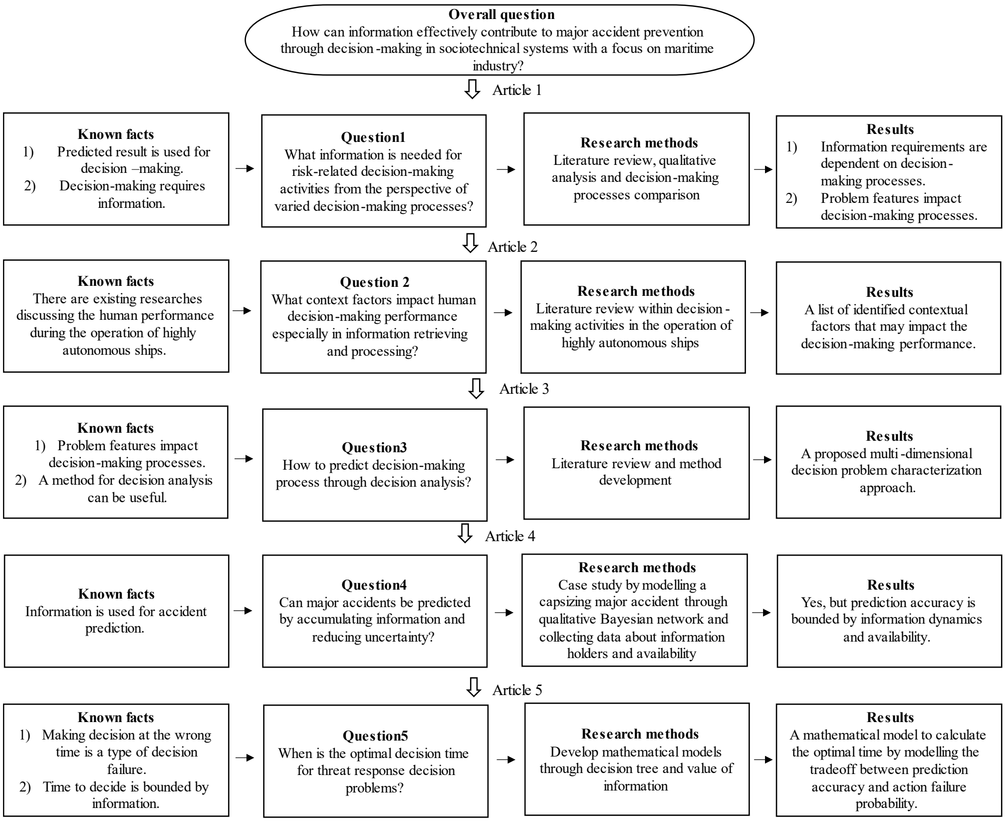

Figure 5-1. An overview of research questions addressed in the thesis, together with their premises and main results

5.1 Article 1 – The need of information in risk-related decision-making activities

Article 1 addresses the issue of information requirements for making risk-related decisions. First, the relation between information, prior knowledge and decision-making is clarified. Afterwards, a new definition of risk information is proposed. This article also propose that information needs in decision-making are related to two dimensions: decision problem and the decision-making process deployed to resolve the decision problem. By analyzing the knowledge state of each group decision-making process, 5 types of needs of risk information are summarized and obtained.

5.1.1 Information and decision-making relation clarification

To study the need of risk information for decision-making, we need to recognize the role of prior knowledge and new information first. Following the information-processing theory of problem-solving, information and prior knowledge of the decision-makers are the inputs, and a chosen solution is the output. The sources of information are external environment, while the sources of prior knowledge are the decision-makers' memories. The need for new information implies that there is a deficiency or anomaly in the decision-maker's state of knowledge so that the decision problem cannot be solved; this deficiency or anomaly triggers information-seeking behavior. Accompanied with information requisition, the state of knowledge changes so that a decision can be made or in another words the knowledge gap can be closed to a satisfactory degree.

If we say there is a state of situational knowledge which contains all forms of knowledge associated with the decision problem, then the decision-making process is also a situational knowledge gaining process because the knowledge of decision-makers changes from initial state to a new state with information acquisition. Further, the study of information need is also a study of situational knowledge requirement. Risk information is part of all information that are needed and used to close the knowledge gap along with the decision-making process, as illustrated in Figure 5-2.

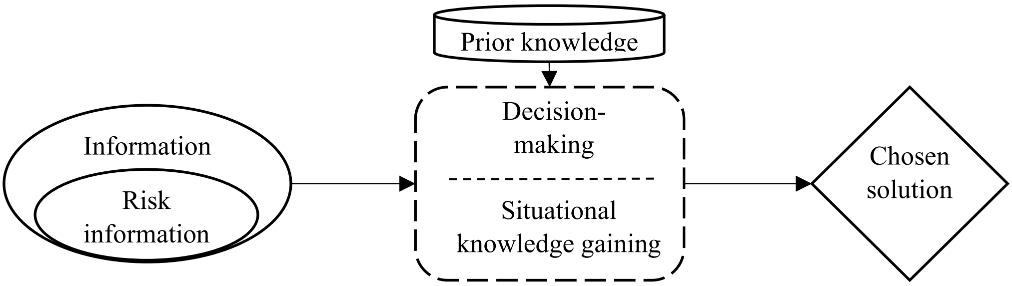

Figure 5-2. Risk information, knowledge and decision-making (from article 1)

5.1.2 A proposed definition of risk information

Following the clarified relation between knowledge, information, and decision-making, risk information is therefore defined as any information that is used to achieve an improved state of knowledge about risk as a basis for making a risk-related decision. The sources of information can be the environment, digital system, colleagues etc. The proposed definition of risk information is more than plain risk numbers or risk matrixes or other direct expressions of risk. There are at least 4 categories of risk information:

- Direct expressions of risk, including risk measurements, expected values, probability distributions, consequences, hazardous scenarios, risk indicators, qualitative descriptions.
- Indirect expressions of risk, for example, factors which influence risk, stop criteria, constraints, distance to the stop criteria and constraints.
- Information about how risk is interpreted and estimated, including the input data, assumptions and the process.
- Information that represents the relevance, completeness, and accuracy of the information mentioned above. This category expresses the quality of the information, which is named as meta-information.

5.1.3 A proposed framework to identify information needs

There is a high diversity in risk-related decision problems. The presence of a decision problem is situation and objective specific. There are different processes for resolving the decision problem also. Two dimensions of factors that influence the information needs in decision-making are suggested: the problem dimension and the decision-making process dimension. Figure 5-3 gives the simple and conceptual representation. Specific factors are outlined from those two dimensions. They are:

1) Identity which is determined by decision-makers' tasks and job responsibilities.
2) Changes of problem due to development of situation, including the change of decision-maker's definition of risk and values.
3) Features of the problem which are the distinctive attributes or aspects of the problem.
4) Prior knowledge of the decision-maker who are responsible for the decision problem, including bias, experience improving or skill degradation, training, awareness.
5) Environmental factors such as attention, distraction, established interaction patterns, information availability and accessibility which can be dependent on the organization's information environment, external requirements, time constraints from internal or external stressors, cognition load, and relative importance of the risk-related decision problem compared with other problems which exist at the same time.

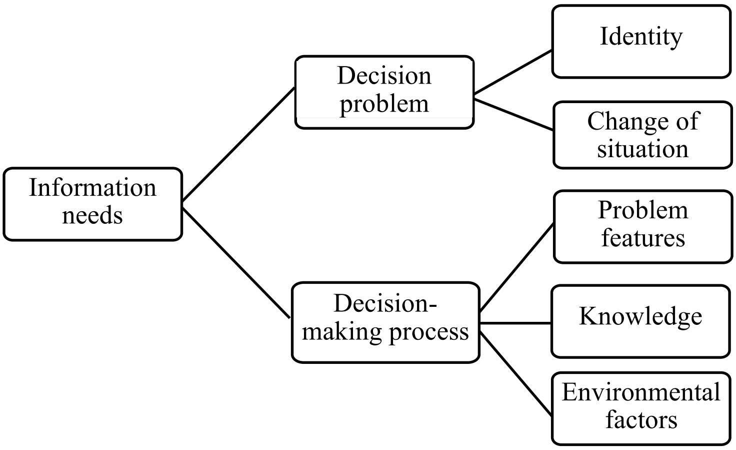

Figure 5-3. Two dimensions for identifying information needs (from article 1)

These factors can be interlinked to some degree. For example, a certain task may have some specific features (the degree of complicatedness, etc.) and the environmental factors (time constraints, distractions, etc.). In addition, some decision problems may demand a certain type of decision-making process. It can be interesting to further examinate the mechanisms between factors and decision problem/decision-making process, whether there are interrelations between those factors.

5.1.4 A classification of information needs in decision-making

It is found that the information requirements are not the same for different types of decision-making processes. The differences stem both from the type and the amount of information requirement. Bounded-rational decision-making process requires the most information while intuition-based decision-making process requires the least. Information needs for pattern-recognition based decision-making process is reduced by decision-makers rich prior knowledge in the memory. Instead, relevant cues to trigger problem recognition is required so that the type of information is also altered. Rule information is only required for rule-based decision-making process. Overall, we conclude that information is required to generate knowledge about:

1 The current situation for problem identification and detection.
2 Contextual factors, which allow to 1) evaluate the relative importance of a decision problem for resources (e.g., attention) allocation, and 2) judge how to resolve the decision problem.
3 Possible solutions (options, a course of actions).
4 Predicted possible consequences of a potential option or solution or predicted possible consequences of a potential option or solution.
5 Constraints that are used for comparing and evaluating alternatives or evaluating solutions.

6. Rules which are set to guide actions.
7. Goals or sub goals and objectives. For example, projected objectives and associated preferences of various stakeholders, which allows each potential choice to be evaluated and compared to alternatives.
8. Identity and associated responsibilities.

An information need gives recognition that there is an anomaly in the user's state of knowledge concerning one or many items listed above. To reduce uncertainty or close the knowledge gap, at least four strategies can be applied: 1) searching for existing information, 2) confirming or discarding information by using other information sources, 3) using existing information to form new information by analogy or inference, 4) testing and interacting with the system environment to get new information.

5.1.5 Proposed types of risk information requirements for decision-making (the roles of risk information)

By considering the proposed definition of risk information and information needs of the various decision-making processes, we conclude that the needs for risk information for risk-related decision problems can be classified into 5 types. Each type represents a form of risk information with a specific function (to generate a specific type of knowledge) in decision-making. The risk information requirements are not the same for each type of decision-making process.

Type 1 is the information about existence of risk-related decision problems for problem detection and identification. Such information can be a direct expression of the safety problem or an indirect expression but sufficient for the decision-makers' inference of the problem. It also includes information which reflects the if-conditions of a certain rule.

Type 2 is the information about contextual factors. This could be e.g., information about the severity and urgency to decide. This information helps the decision-maker judge how to solve the decision problem including how much effort should be put into resolving the decision problem and how fast the decision should be made.

Type 3 is the information about constraints, system boundaries, specifications, and requirements of workable solutions. This group of information can be classified into three subtypes according to their functions: 1) Safety margins and operating limits; 2) Information about requirements for workable solutions and availability of required resources, such as money, time, space, a special skill, or a certain system/subsystem condition that is required for an action to be feasible; 3) Cause-effect relationship between a proposed solution and possible outcomes.

Type 4 is the information about attributes of alternatives for comparing and evaluating. A decision-maker needs to make a judgement based on Type 4 information on which alternative is going to achieve the maximum benefits. For example, decrease/increase of risk or probability of introducing hazards/undesired events of the alternative sets.

Type 5 is information about rules that are set to maintain safety or control risk, such as procedures, rules, and standards. These rules can guide actions under certain circumstances for decision-makers.

5.1.6 Discussion

The goal of article 1 is to try to solve the problem of needs of risk information for the problem-solving activities of risk-related decision problems. In the context of this article, information needs are analyzed from the dimension of decision-making processes. One may argue that the results represent theoretical information needs but not actual information needs. Difficulties still exist in retrieving the actual knowledge requirement which can be individual/group and situation specific. This is where the proposed framework of information needs comes into play. The individual/group and situation specific information needs can be further studied using the proposed framework.

The study of information needs is meaningful due to the normal contextual factors which constrain decision-makers' access to infinite information or infinite time to search for information or creating the proper knowledge. Even though decision-makers are actual information seekers, who is continuously looking for what is missing, what they can find is determined by the setup of working environment. Therefore, the research result will contribute to the design of knowledge environment, including information system, which can be a type of information-based strategies. When it comes to information acquisition, balancing the accuracy, cost and efficiency in information retrieval can be further researched. Further, research about information needs may increase our understanding about how organizational factors contribute to the occurrence of accidents, because organizational factors impact decision-makers' behavior, then indirectly they will also impact system safety.

The way humans interact with the sociotechnical system is through decision-making and action implementation cycle. During decision-making, there are two main predictions. One is the prediction of system behavior without extra action intervention; the other is the prediction of action effects. The most difficult type of risk-related decision problems is likely to be those contingent but critical ones, such as the problematic situations before the onset of a major accident. Sensemaking-based decision-making process might be the relative plausible one comparing with other groups of decision-making processes. Handling them well can be difficult due to the challenges from very limited availability of time, experience, knowledge, applicable rules. However, sensemaking is directed by plausibility from decision-makers and not necessary accuracy. The possible solutions for handling those type of critical situations can be: 1) directing an accuracy guided sensemaking in decision support; 2) making a fast analytical tool to project the future and tell the operators the requirements of workable solutions (for example, how long time until the critical thresholds are exceeded) and this fast analytical tool must have been prepared and available all the time; 3) preventing the occurrence of those situations ahead so that there is no need to face them.

5.2 Article 2 – A holistic review of factors which challenge decision-making performance

For accidental scenarios like ferry capsizing, humans will still be the one in charge even though more and more system functions or subfunctions become automated or even autonomous. Those remaining and added decision problems are critical and complicated. Article 2 reviewed human factor related issues in the context of highly autonomous ships' operation. The performance of human decision-maker essentially depends on the three phases of a decision-making process: 1) problem recognition, 2) determine a satisfying action timely, and 3) correct and timely execution in accordance with the decision. Working contexts pose challenges to the three phases. The revealed main contextual factors are level of autonomy design, remote operation, transition of operating modes, collaboration between crews and autonomy, teamwork between crews, goal and sub-goal omission, operation rules following, uncertainty, mental constraints and characteristics, and changes during operations. A holistic integrated descriptive representation of those issues in relation to the three phases of decision-making is provided also, as shown in Figure 5-4. Many of those identified issues pose threats for problem recognition rather than decision-making and action implementation. This may imply that problem recognition is more fragile than the other two phases. The proposed integrated representation of human factor related issues and problem recognition - decision-making - action process can be further refined and developed into a model for qualitative or quantitative analysis.

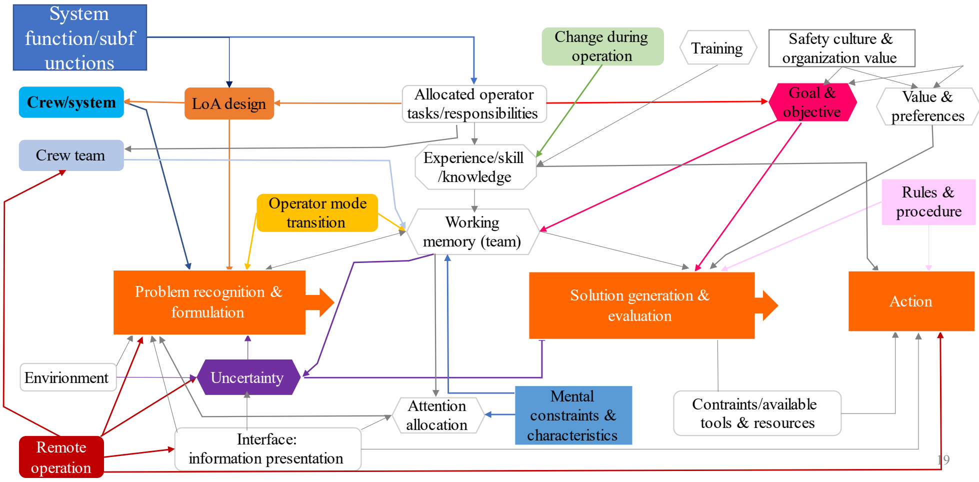

Figure 5-4. Integrated representation of human factor related issues (modified from Fig. 4 in article 2)

5.2.1 Discussion

This article is a literature review which summarizes existing research results and discussions about human factors related issues in the operation of highly autonomous ships. A few of the reviewed studies are based on experiments on simulated environments while others are based on interviews or expert knowledge. More empirical research will be needed both for the verification of current knowledge and for promoting the depth of knowledge.

This review study reveals several aspects of working context that can impact the human performance. The holistic representation links those macro aspects of the working context to the micro aspects in the decision-making process. It gives general guidance on what one should pay attention to in design and operation to improve or at least maintain human performance.

However, the review is taken at a general perspective instead of being decision problem, or decision-making process specific. Imaginably, there will be different decision-making processes that might be deployed, and many decision problems that human operator needs to solve. The working context might be favorable for one but undesirable for another. Further research will be needed if one need to evaluate the performance for a specific critical task or decision-making process.

5.3 Article 3 – Characterization of risk-related decision problems

The term "risk-related decision problem" is defined in article 1; and the decision-making process that is deployed to solve the decision problem will indicate the information needs. It is also stated that which decision-making process will be deployed is dependent on problem features, prior knowledge of the decision-maker and environmental factors. Therefore, Article 4 is aimed at developing an approach which can facilitate a better understanding of the features of the decision problem. An improved analysis of risk-related decisions can potentially be achieved by using the proposed approach. Such analysis can support the prediction of the human decision-making process, potential decision errors, and the identification of decision support requirements.

5.3.1 A proposed multi-dimensional approach

A multi-dimensional approach is proposed to analyze the features of risk-related decision problems. The proposed dimensions for characterization are:

1. Criticality. This dimension describes the degree of criticality ranging from "negligible" to "critical". The degree of criticality is determined by the potential consequence (threat to safety) if the problem is not properly solved. The criticality can be evaluated by a combination of 1) the importance of the safety objective, 2) the size of the gap between the actual and desired states, and 3)

the proximity to hazard (pressure from the exposed danger). Degree of criticality implies the how much resource or attention should be spent in solving the decision problem.

2. Uniqueness. This dimension describes the degree of uniqueness ranging from “common” to “unique”, which is the occurrence frequency of the decision problem. Degree of uniqueness implies whether we can directly copy existing solutions.
3. Structuredness. This dimension describes the degree of structuredness ranging from “well-structured” to “ill-structured”. It describes the degree of consensus about which values, and information are at stake during problem-solving. The degree of structuredness implies whether we should focus on problem structuring or resolution.
4. Complicatedness. This dimension describes the degree of complicatedness ranging from “simple” to “complicated”. The degree of complicatedness is measured by the number of information items in the problem statement including the number of elements in the problem space. The number of information items is a sum of the number of possible future states, number of objectives, number of possible courses of action which can equally be the number of possible causes, number of constraints, and the relationships between the variables. The degree of complicatedness implies whether it exceeds our process capability and whether problem decomposition or further abstraction is needed.
5. Dynamic. This dimension characterizes the changing and developing property of the decision problem, ranging from “static” to “dynamic”. The degree of dynamic implies how frequent we should monitor the gap and how fast we should respond.
6. Problem trigger. This dimension is about the origin of trigger of decision-making activity which can be “proactive” or “reactive”. Problem trigger (Reactive or proactive) implies where we should monitor for problem detection.
7. Residual uncertainty. This dimension describes the degree of residual uncertainty (available knowledge in the world) in terms of the variables in the problem space, such as knowledge about further development of the problem and possible solutions. The degree of residual uncertainty ranges from “low” to “high”. The degree of residual uncertainty implies how robust or precautious our solution should be.

In Article 3, 2 examples are used to illustrate the proposed approach and its implication. One case is the iceberg threat handling for an FPSO (Floating Production Storage and Offloading unit) installation manager, the other is the COVID-19 problem for an individual. In addition, we also tried to map typical risk-related problems by the proposed dimensional approach. Each problem type has a different value in each dimension. For example, design problems are characterized by high degree of residual uncertainty and ill-structuredness, while being static and proactive. Problem characterization can also help us to understand a certain type of decision problems. Decision support can first meet the general features of the problem type and then extend to meet the demand of an individual decision problem.

5.3.2 A proposed visualization tool

A qualitative radar map is also proposed to give an overview of the problem features. Figure 5-5 is an example taken from article 3 which shows the features of an iceberg collision threat problem. The outward angle means that the specific dimension requires more attention and the specific type of support or a certain decision-making strategy, e.g., if a problem is highly dynamic, decision-maker will/should respond fast to it. The size of the heptagon indicates the difficulty level in resolving the problem, and the degree of required external support. The larger the heptagon, the more difficult will the problem-solving be and it will be more likely to end up with a poor performance if the implemented decision-making strategy does not meet the demand.

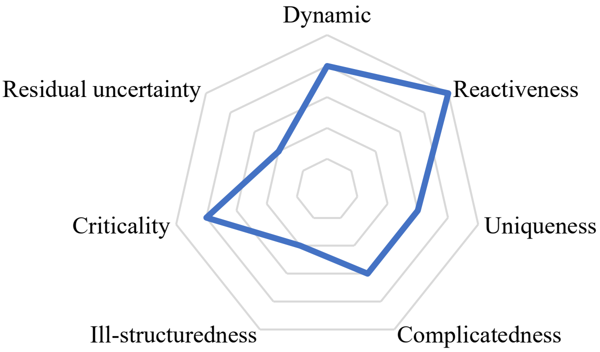

Figure 5-5. Radar map to characterize the iceberg collision threat problem (from Article 3)

5.3.3 Discussion

Applying the proposed multi-dimensional characterization approach can give an improved understanding of the features of decision problems. For designers of decision support, the improved understanding can support the prediction of decision-making process and make decision support more accurate and practical. For decision-makers, it can provide indication for how to solve the decision problem. The analysis of the decision problem can potentially provide feedback for problem formulation also. For example, the decision-maker can reformulate the problem if it is found that the problem is too difficult to solve after characterization. Research may be needed to further explore this idea. In addition, the proposed dimensional approach can also provide insights for training and risk analysis. As risk analysis is always conducted to support decision-making, an improved understanding of problem features can give input to selecting risk analysis methods.

A limitation of this research is that only limited cases are used for illustration. More real-life problems should be investigated to test the reliability and practicability of the proposed approach. Further research can be done to investigate 1) whether some dimensions are more important than others, 2) whether a certain dimension can be subsumed under another so that there is a sequential order of dimensions in problem characterization, 3) whether it is possible to quantify each dimension and how to quantify and scale each dimension.

Another issue, which has not been addressed in this work but is worth study in future, is about how to specify and distribute goals for distributed decision-making in complex systems (Vollmeyer, Burns et al. 1996, Burns and Vollmeyer 2002, Trumpower, Goldsmith et al. 2004), because a decision problem is defined by a gap between the true state and the desired state, namely the goal. Existing research about function allocation and problem statement has similar focus on goal specification and distribution. Research about goal specification is not only meaningful for human decision-making but also meaningful for the design of automation in complex systems, especially when accidents are understood as control failures.

5.4 Article 4 – Verification of possibility of major Accident prediction with a capable accident model and information available.

In article 4, a ferry capsizing accident is studied to investigate accident development and prediction with information available over time. The accident development becomes clearer after critical signals are integrated into the capsizing accident model. Figure 5-6 gives an overview of the capsizing development chain. The result from the case study verified the hypothesis that the accident conditions can be identified before the accident occurs through the accident model and available data. The knowledge to confirm that capsizing may occur or not thus increased with time.

The investigation of information available with time shows that 1) some indications were available long time before the accident; 2) events, which contributed to the development of accident, happened at different times and involved different parties; and 3) a prediction can always be made, however the accuracy can be questioned due to the information availability with time.

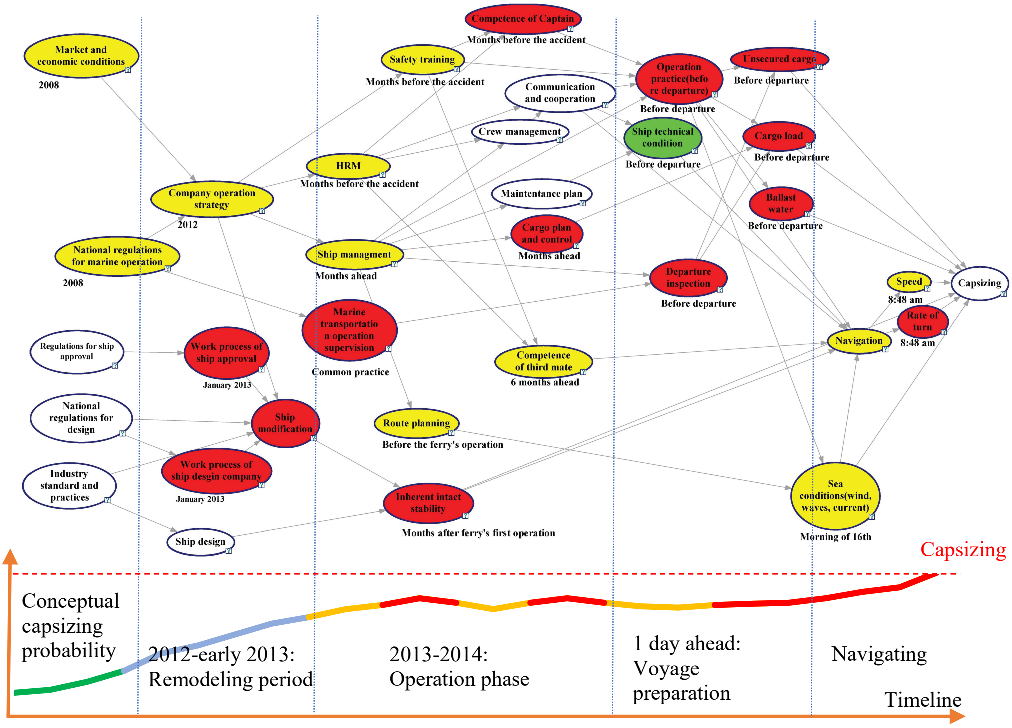

Figure 5-6. Result of article 4: The accident prediction by integrating available information about the MV Sewol capsizing into the developed capsizing accident model

The investigation of the different information holders shows that the persons who oversee design and modification may not be the same one who is responsible for the operation. The design issues which were identified during the operation phase may not be responded to or solved in a proper way, especially if the design has been approved even with mistakes. The people in charge on the top usually have the widest coverage of information. However, they will normally not know all the details, thus an overview cannot be achieved. The study also verifies again what Rasmussen (1997) has pointed out. Within the company, tasks are distributed across different departments or just different people. Each department or person generally has different goals and considerations according to their duties in the company. They push each other and cooperate at the same time. The safety boundaries or limits are breached without being noticed.

The developed capsizing model is a qualitative model. It is possible to develop the qualitative model into a quantitative one. In addition, it can be further improved and expanded to cover more details and used for similar types of accidents. The developed accident model can assist managers in gathering data for risk monitors and accident prevention in practice. However, further research about the practice of information collection and processing is required. Challenges stem from 1) the wide spreading of information sources among different people and stakeholders over time; 2) the difficulty to evaluate the diagnosticity of information regarding risk or accident both due to the aging of information and causation ambiguity; 3) the challenge to ensure the reliability of data reported with in a bureaucratic system without a good safety culture; etc.

5.4.1 Discussion

The function of making a prediction is to identify if there is a need for a decision-making activity so that relevant response action can be taken. The correct response action may not be the same for different capsizing scenarios. The developed capsizing model only present one type of scenario of capsizing while several different scenarios may occur for capsizing and different types of accidents may happen during ferry operations. Potentially, this will lead to large numbers of possible accident models and predictions; The ambiguity between accidental scenarios will be increased. Therefore, it is important to identify the correct situation and exclude out the impossible ones or extremely unlikely ones and focus on the possible ones so that the correct response action is taken. Establishing a way to discriminate scenarios and match up with the true accidental scenario can be a topic for future research.

As we know, major accidents happen rarely. Data samples are limited not only for prediction model development but also for prediction reliability evaluation. Explanatory knowledge is counted for model development. As for prediction reliability evaluation, it is challenging to answer the unavoidable questions such as “When can the prediction be trusted?”, “What is the minimum performance requirement of prediction?”. In addition to the challenges coming from the normative perspective of decision-making, challenges also come from the descriptive perspective such as professionals do not do math but trusting their gut feelings and the psychological perspective such as the information avoidance phenomena that people avoid seeking information about hazards and pretend to be blind about things they do not want to see. Further research will be needed to overcome those challenges.

5.5 Article 5 – A proposed approach to optimize the timing of threat response

Making decisions at the wrong time is a type of human error. Article 5 presents a value of prediction (VoP) model to calculate the optimal time to decide for threat responses, which is called optimal responding problem in the article. The article formulates the “optimal responding problem” and its solution through probabilistic mathematics; it provides a unified manner to describe and solve the problem and enables a general application of the solution and can be used further for automated decision-making.

Threat response is a typical type of risk-related decision problems. For a threat that evolves during an incubation period and materializes with a likelihood, prediction about whether it will materialize is a main determinant for response action. As discussed in article 4, accident prediction requires information input, and the prediction accuracy is bounded by information dynamics and availability and has a time-varying accuracy. Article 5 proposes that the time to decide is when there is no more information that gives a more reliable prediction to compensate for the postponement. The proposed value of prediction (VoP) model is based on information value theory and resembles the tradeoff between prediction accuracy and action failure probability over time. Figure 5-7 illustrates the relationship between cost and response time.

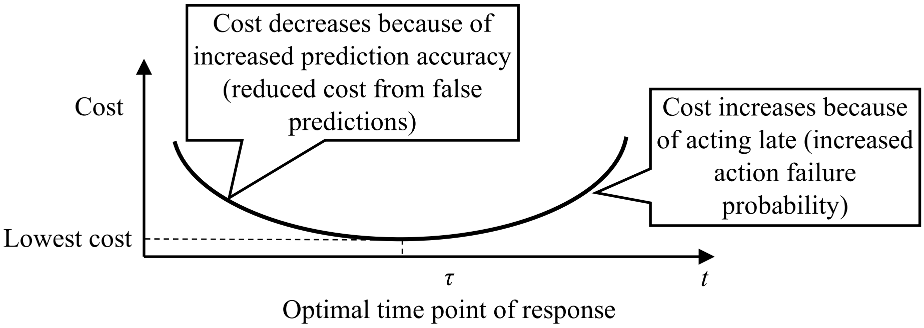

Figure 5-7. Illustration of trade-off between prediction accuracy and action failure probability over time (from Article 5)

The results show that it is not always beneficial to postpone responses and wait for more information except when the cost ratio between accident and the response action is moderate. Thus, decision-making is easy when it comes to severe consequences or small losses. If the accident consequence is severe, the decision-maker should be precautionary and take the response action as early as possible, while the decision-maker can ignore the risk and do not need to take any response action if the accident consequence is small.

The prediction accuracy of different prediction horizons (how far into the future that the prediction is) has an impact on optimal response time. However, the impact is limited and dependent on how sensitive the prediction accuracy is over the prediction horizon and how fast the response accuracy decreases with time available. The response strategies will be in contradiction with each other for the two extreme cases:

1) Prediction accuracy does not increase for shorter prediction while failure probability increases fast.
2) Prediction accuracy increases quickly while failure probability does not increase.

In the first case, it is better to respond as early as possible if the risk from the threat exceeds the tolerance threshold. For the second case, it is better to postpone and respond late as long as there is enough time available for the response action.

In addition, taking the strategy of multiple prediction and a series of actions (redundant responses) can achieve a higher degree of cost reduction than a single action especially if the accident is severe. The risk can be maintained at a low level even for a threat which can cause severe consequences when it is possible to take multiple predictions and a series of actions which means that optimizing a series of responses including both the sequence of actions and time of each response can give both a low risk level and high efficiency.

Major accidents are not common event. Very likely, one can only achieve partial predictability; prediction accuracy is not 100%. The proposed VoP model can also be used to answer questions such as: When can we rely on our imperfect predictions? How good must the prediction be to be usable or provide additional value? What is the risk threshold between making decisions based on prediction and making decisions without prediction (such as taking a precautionary approach or simply tolerate the risk)? What is the risk threshold between responding now and later? How much should we invest in prediction? How much can we invest in the response action?

The results also show that when partial predictability is involved and provide a positive value, risk can be reduced; the minimum accident cost (risk tolerance threshold) for taking the preventive action is also reduced; and the maximum response investment is raised. Therefore, a prediction model can still be useful and trusted even though it is not perfect.

5.5.1 Discussion

Starting from the idea that the time to decide is bounded by information available, article 5 proposed a probabilistic mathematical utility model to calculate the optimal time point to make threat response decisions. The proposed model can optimize time to decide because it links the time dimension with decision-making output utility through information dynamics and its resultant prediction accuracy. The proposed model can also be used to infer: 1) whether prediction should be trusted; 2) prediction performance requirement; 3) thresholds between “ignore the risk”, “predict and respond accordingly” and “be precautionary”; 4) maximum response investment.

One inference can be made from the mathematical model is that information produced from imperfect prediction can reduce risk, at the same time lower the risk tolerance threshold and raise the maximum response investment.

Some simplifications are made in the modelling. First, it is assumed that the prediction cost is negligible compared with accident cost and action cost. This may not be true in some cases, such as when it is expensive to obtain the input measurements the prediction model or expensive to construct a useful model. A prediction cost can be simply added to the calculation when necessary. If so, one possible conclusion will be that it may also be rational to stay ignorant and do not take input data if the cost to obtain input measurements is high. Then potentially, the cost function can be further used to allocate sensors.

In addition, accident cost and response action cost are assumed to be known and constant. The model can be extended further considering those costs as varying instead of being fixed. For example, information dynamics about accident consequence which can be reflected by prediction accuracy about accident severity can be included. That is done by including a prediction model and its error matrixes of a series of prediction horizons for accident severity. The same applies to other known variables in the model. A refined optimal response time and action can be obtained. However, the drawback is that the model will become complicated because the number of variables will expand exponentially.

6 Conclusion

This thesis has explored 5 questions around the concept of information-based strategy to facilitate an effective information utilization for major accident prevention. The overarching problem and sub questions addressed are listed in Table 6-1. The findings from addressing the 5 questions are summarized in Section 6.1. Implications of the findings are summarized in Section 6.2. Future research needs are described at the end.

Table 6-1. Research questions

How can risk information effectively contribute to major accident prevention through decision-making in sociotechnical systems with a focus on maritime industry?
1) What information is needed for risk-related decision-making activities and specifically what types can be called risk information among all the information requirements?
2) What context factors impact human decision-making performance especially in information retrieving and processing?
3) If information needs vary and are dependent on decision-making processes, is there a way to predict decision-making process through decision analysis?
4) Can major accidents be predicted by accumulating information and reducing uncertainty?
5) How is the optimal decision time for threat response decision problems bounded by information availability?

6.1 Findings

To facilitate an effective information utilization for accident prevention, it is critical to understand what the information requirement is. To understand the information requirement, the relation between information, knowledge and decision-making activity needs to be clarified.

A need to redefine risk information has been articulated. A new definition of risk information is proposed, as follows:

> *Risk information is any information which is used to achieve an improved state of knowledge about risk as a basis for making a risk-related decision.*

A framework to analyze information needs is also proposed, which says that the information needs can be understood by analyzing decision problems and the decision-making processes. Correspondingly, the kind of decision problem which arises depends on the identity of the decision-maker and the situation; the kind of decision-making process that will be deployed depends on the decision-maker's prior knowledge, problem features, and environmental factors.

It is found that the right risk information is needed to form knowledge about 1) the existence of a certain risk-related decision problem, 2) context factors such as the severity and urgency of decisions, 3) requirements and constraints of workable solutions, 4) attributes for comparing and evaluating solutions, and 5) rules to maintain safety or control risk. Furthermore, accident prediction as a risk information source has a function for problem detection and identification.

For the operation of highly autonomous ships, human decision-makers will still play a critical role in solving complex and emergent problems. The literature review reveals that many context factors may impact decision-makers' performance in solving those complex and emergent problems. Those context factor include but not limited to level of autonomy design, remote operation, transition of operating modes, collaboration between crews and autonomy, teamwork between crews, goal and sub-goal omission, operation rules following, uncertainty, mental constraints and characteristics, and changes during operations. Many of those context factors impact problem recognition phase for which information input is crucial. Managing input information for decision-making is the key to maintain task performance and system safety. Thus, to ensure human performance in solving complex tasks, it is necessary to understand the information requirements in decision-making.

Under the condition that sociotechnical systems are running in a distributed manner, there is a high diversity in risk-related decision problems. Those decision problems have certain features. Together with the understanding that a decision problem's features have implications in assessing the sensitivity and appropriateness of decision-making processes, there is need of a method to predict the decision-making process.

Consequently, a multi-dimensional problem characterization method is proposed to analyze decision problems. Seven key dimensions are defined for the characterization of risk-related decision problems. They are criticality (negligible to critical), uniqueness (common to unique), structuredness (well-structured to ill-structured), complicatedness (simple to complex), dynamic (static to dynamic), problem trigger (proactive to reactive), and residual uncertainty (low to high). A qualitative radar map is introduced also to visualize the problem features and work as a decision support tool. For a decision-maker, an improved analysis of the decision problem can give a picture of which aspects of the decision problem need more focus and therefore may enable a better strategy in solving the problem and hopefully lead to a better solution. In addition, it can potentially work as an alternative approach to handle risk-related problems.

Accident prediction provides input information for relevant decision-makers so that preventive action can be taken ahead. A try-out prediction about MV Sewol ferry capsizing accident has been conducted. For the try-out prediction, a capsizing accident model was developed. Pre-warning information availability with time and holders for MV Sewol accident were investigated and integrated into the accident model. The try-out study shows that accidents can possibly be predicted. Results shows that the available information was widely scattered in different information holders and became available at different times along a wide time spectrum. For decision-makers at the sharp end, it can be challenging to have overview across the many information holders and the wide time spectrum. This indirectly support the information-processing perspective of accident causation which says accidents happen due to a lack of right information, so that threats are not handled timely or correctly.

Threat handling is a typical type of risk-related decision problem. Response action must be taken ahead before accident occurs with or without prediction of accident occurrence. When to decide, is a problem which needs to be answered for time-sensitive threat handling tasks to avoid decision failures. It is found that decision time for threat response is bounded by information availability and prediction accuracy.

A "Value of Prediction (VoP)" model based on information value theory is developed. It is demonstrated how the VoP model can calculate the optimal timing of response considering the trade-off between prediction performance and action failure probability over time. As a result, the optimal timing of response is dependent on the ratio between accident cost and response action cost, accident probability, action failure probability, prediction performance, and response strategy (a series of sequential responses). An optimization of response times and response strategy by considering sequential responses can maintain a low risk and high efficiency level. However, prediction does not always provide added value in accident prevention. When accident consequence is extremely high, it is better to be precautionary and act as early as possible when the lowest failure probability is guaranteed, rather than relying on predictions. When the consequence is comparable with the cost of response action, it is rational to ignore the risk. Calculating optimal response time based on VoP is supportive for threats which pose a moderate cost. However, it is improper to ignore partial predictability because partial predictability can push down the threshold of risk acceptance and raise up the threshold of being precautionary and maximum response investment.

To conclude, a series of related questions have been discussed in this thesis. Theories are proposed, approaches are developed. Information can contribute to accident prevention because:

1) It reduces uncertainty which is one of the sources of risk.
2) It is a necessary input for risk analysis, accident prediction etc.
3) It is a necessary input for solving risk-related decision problems, including signaling the existence of risk-related decision problems and ensures decision-making quality.

Effective utilization of risk information for major accident prevention through decision-making in sociotechnical systems can be improved by:

- Understanding the information behavior, including information needs, of decision-makers when making risk-related decisions.
- Understanding risk-related decision problems that may arise.
- Understanding the features of the risk-related decision problems and possible decision-making process.
- Understanding the factors that may impact the information behavior and decision-making performance.
- Applying accident prediction and/or risk analysis models which can integrate information from multiples actors in sociotechnical systems.
- Understanding when to make decisions with imperfect predictions.

6.2 Implications

The implications of the PhD research can be seen from: 1) established concepts and definitions, 2) discovered facts, 3) proposed approaches, 4) results from case studies.

This thesis proposes a concept of information-based strategies for accident prevention. The concept is underbuilt with thorough reasoning for why information can contribute to accident prevention. The proposal could raise attention and unlock potentials in both academia and industry to develop such type of strategies to further reduce risk and make the society safer. The concept can also promote more effective utilization of information, which the advancing technology produces more daily. The synchronization of decision-making and problem-solving, proposed definition of “risk information” and “risk-related decision problems” clarify concepts for industry application and can promote further research along the proposed information-based accident prevention strategies.

The proposed theoretical and analytical framework for systematic elicitation of information needs can facilitate future research and industrial practices that intend to ease the problem of information deficiency in decision-making by designing improved information/decision support system.

The findings about the roles of risk information confirm the importance of risk information in resolving risk-related decision problems. Furthermore, they emphasize how risk information can/shall be used for accident prevention and provide the insights for the information support design. An improved information support can contribute to reduction of decision-making time and costs. More importantly, it can potentially improve decision quality and performance, and ultimately avoid major accidents.

The findings about context factors which impacts the decision-making performance of operators during the operation of highly autonomous ships can be used to 1) to understand the potential challenges that could threaten the safe operation of autonomous ships, 2) guide the direction in solution searching to improve decision-making performance.

The proposed qualitative decision problem analysis approach can be used to obtain an improved understanding of risk-related decision problems. An improved understanding can assist prediction of decision-making process and information requirements. In addition, an improved understanding can also provide insights for training and risk analysis method selection.

The verification of major accident condition prediction encourages development of accident condition prediction models and information gathering from multiple actors and sources. In addition, high inaccuracy in long-term prediction may make results insufficiently reliable to support operational decisions, but inaccuracy can be reduced by short-term prediction. Such gives a hint about balancing the usage of long-term prediction and short-term prediction.

The proposed VoP model can be used to: 1) Calculate the optimal time point to make threat response decisions so that risk can be minimized; 2) whether prediction should be trusted; 3) prediction performance requirement, 4) boundary between "ignore the risk", "predict and respond accordingly" and "be precautionary"; 5) maximum response investment. The mathematical model provides evidence that information produced from imperfect prediction can 1) reduce risk, 2) lower the risk tolerance threshold, and 3) raise the maximum response investment. This finding provides rationale for the practice of hazard detection, accident prediction and prognosis, and risk monitoring.

Across the whole PhD work, 4 case studies are conducted. The case studies are developed from real scenarios. Thus, the results from case studies can provide valuable information for those who are stakeholders of similar scenarios.

Overall, the results contribute to build up the theoretical foundation of information-based strategies for accident prevention and promote more effective utilization of information for accident prevention in the future. For the industry, the results can be used to support implementation of hazard detection, accident prediction and prognosis barriers, resolving risk-related decision problems, design of decision support systems in complex collective modern work environments, design algorithms to solve risk-related decision problems, design of digitalization etc.

6.3 Further research needs

Further research needs are summarized from several aspects. First, future research is required for further verification of the proposed theories and approaches, for example, by using a different approach or testing through applications. Second, within the PhD research work, many simplifications and assumptions are made thus the results are conditional. Further research can be done to examinate the results if the simplification or assumptions are lifted. Third, further research can be done to solve the issues and to achieve the potentials revealed from this PhD work.

The framework to analyze information needs is proposed based on reasoning. There is a need to further test the framework by other methods to check its validity and feasibility for application.

Study presented in article 2 reveals the several aspects of working context including information environment that can impact the human performance. Due to the lack of empirical research among existing studies, more empirical research, such as by conducting experiment in simulated environment, will be needed both for the verification of current knowledge and for promoting the depth of knowledge to understand the impact of working context on decision-making performance. Investigation can possibly start with a specific type of tasks and gradually extend to a large scope after a good research practice is established. Further research can be done to refine and develop the proposed integrated representation of human factor related issues and problem recognition - action determination - action implementation process into a model for qualitative or quantitative analysis.

As for the proposed multi-dimensional characterization approach, only limited cases are used for illustration. Further research is needed to test the reliability and practicability of the proposed approach. In addition, in-depth research can be conducted to check 1) whether some dimensions are more important than others, 2) whether a certain dimension can be subsumed under another so that there is a sequential order of dimensions in problem characterization, 3) whether it is possible to quantify each dimension and how to quantify and scale each dimension. Another research task is about goal specification because the framing of decision problems is tightly connected to goal. Scenarios, where decision problems sit, can be quite complex which cannot be defined by one parameter. How to formulate the goal in accordance with the real situational parameters need to be further clarified. Such is also relevant to hazard description and detection, recognition and understanding of new signal.

It can be argued that the study conducted in article 4 is a hindsight because the analysis is done after the accident occurred instead of before the accident occurrence. Therefore, the prediction possibility should be verified further. In addition, prediction reliability should be measured as an input to determine how to use the predicted result. The aim can be altered from predicting major accident to predict one or multiple underlying conditions of the occurrence of major accident to increase the size of data samples. In addition, further work is needed to develop more prediction models to cover as many accidental scenarios as possible and their corresponding response actions. The prediction model could integrate operational data from multiple sources for accident prediction and prognosis. Discrimination strength of different sources can also be studied. At the same time, discrimination between accident scenarios should be conducted to have an unambiguous forecast so that a correct response action can be taken.

The current cost function for calculation presented in Article 5 considers whether the threat will materialize as the only unknown variable with information dependent prediction accuracy. Further research can be done to extend the model to consider other variables as unknown as well to obtain a refined optimal response time and action. Assuming that predictability is provided by predictors (such as risk-influencing factors), examining how far they can predict and developing corresponding preventive actions can provide a basis for automated decision-making to maintain a low risk level. In addition, future work can be done to quantify the relation between the action success probability and time available and/or other condition variables.

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Part II

Research Articles

Article 1

Risk information in decision-making: definitions, requirements and various functions

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Risk information in decision-making: definitions, requirements and various functions

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ABSTRACT

Inappropriate decisions are often regarded as causes of major accidents in the process industries. To improve the quality of decisions, it is important to make the right information available at the right time. The objective of this work is to investigate what types of risk information is needed for risk-related decisions in various decision-making processes. A framework is proposed to facilitate future research for easing information deficiency. In this paper, risk information is examined through common decision-making processes, and is identified serving to 1) detect and characterize risk-related decision problems, 2) indicate the severity and urgency of decisions, 3) state requirements and constraints of workable solutions, 4) represent attributes for comparing and evaluating solutions, and 5) act as rules to maintain safety or control risk. These usages of risk information in different decision problems imply the large diversity in information needs for decision-making. An adaptive information support is thus suggested to provide targeted risk information to specific decision-makers for effective and efficient decision-making in accident prevention in the process industries.

1. Introduction

The process industries are complex and highly technological domains, where many sociotechnical systems are involved. Major accident is a critical threat for the process industries. One of the issues that investigators will focus on after major accidents are what decisions lead up to the accidents. For example, the 2010 San Bruno gas transmission pipeline rupture (Hayes and Hopkins, 2014) illustrates that a disaster can be contributed by decisions that were made independently by personnel at different levels of an organization over a long period of time. Several inappropriate decisions were made in this case, from designing inspection programs and cost cutting on maintenance and inspection, to handling specific situations during the operation. Such decisions may be called risk-related decisions.

Undesired consequences from decisions are associated with limited awareness of risk (Vaughan, 1996), poorly structured problems, unclear goals, ambiguity (Kunreuther and Meszaros, 1996) and conflicts between visible cost and uncertain benefits. Those issues are typically intensified by the complexity, ambiguity, uncertainty or insufficiency of risk-related information or knowledge which good information support can help to resolve (Zack, 2007). Even though such information is existing, it cannot be properly used before the following questions are answered, such as 1) what risk information should be provided? 2) at what time? 3) for what decision? and 4) to whom.

So called right information is expected, which can give the decision-maker an understanding of the risk so as to facilitate a good decision-making in the specific situation. The right information, or the information need, can in principle be identified from the gap between knowledge of the decision-maker and a desired state of knowledge for decision-making, including both perceived and unperceived information needs. Giving the handling of iceberg threat to an Floating Production Storage and Offloading unit (FPSO) as an example, if the hull damage is an known consequence from collision to the decision-maker while other potential damages such as damage to positioning system are not, then information about potential hull damage from iceberg collision can be a perceived need while information about other potential damage to positioning system is an unperceived need.

It is a complex issue what information a decision-maker exactly needs. Information needs have been investigated by empirical methods such as surveys, interviews and observations (Ayatollahi et al., 2013). Information-decision-action task analysis has been used to categorize tasks and to identify associated information needs (Allen et al., 1971) for

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drivers. Another approach is first to use empirical approach such as interviews or process monitoring to investigate the way of decision-making (to construct the decision ladder (Rasmussen, 1986)) and then use the constructed decision ladder to elicit the information needs (Ward, 2014) including the correct response strategies (Hassall et al., 2014). The empirical methods are restricted by the existence of observable environment and they are not capable to identify unperceived information needs. So far, we are not able to establish a standard list of information categories that will provide for all decision-makers with all the required information for all their risk-related decisions. A systematic analytical method can have potential to facilitate the identification of risk information needs. Such a method can be established in consideration of two influence factors of information need, the decision-making process and the type of decision problem. This is described in more detail in Section 4.1.

However, challenges exist in developing a systematic analytical method: 1) No clear definition of risk-related decision exists, while several terms with varied implications and scopes are used in literature. 2) The default definition of risk information is oriented by risk analysis, rather than decision-making or information processing (Rasmussen, 1983), where risk analysis is not always needed (The UK Oil and Gas Industry Association, 2014).

In this paper, we will thus focus on:

- Sociotechnical systems (Rasmussen, 1997) in the process industries, which are dynamic and involve interlinked, humans in multiple levels of organization and authority, technology and their environment.
- Decisions that influence major accident risk in such systems.
- How risk information need is dependent on the decision-making process applied.
- Investigating what type of information is required for different decision-making processes.

This paper limits itself strictly in decision-making processes, without considering psychology and personalities of decision-maker and general political mechanisms among and within organizations. Further, we do not go into the discussion of whether risk is subjective or objective (Slovic et al., 2004). Also, in the paper, no consideration will be given to the decision-making processes of teams involved in applying systematic or mathematically based methods of obtaining the best or least risky solution or generating the best ranking of options against a set of criteria in an optimum compromise. Rather, this paper is concerned with factors that support the quality of the decision of individuals participating in the process.

In risk management, whether the decision is good or not is sometimes evaluated only based on outcome, i.e. whether an accident occurs or not. However, in this paper, decision quality is analyzed and evaluated from the process perspective, namely whether the right information is used properly in the decision-making activity instead of from the outcome perspective (whether there is an accident because of the decision) by following the practice in decision analysis (Howard, 2007). This is because:

1) If we consider the outcome perspective, it becomes a retrospective learning activity instead of a prospective supporting activity. If we know the alternative will give a negative unacceptable outcome, we would not choose it;
2) The real outcome is (very often) outside the control of decision-makers once the decision is made;
3) Major accidents are seldom. If only outcomes (whether accidents occur) are evaluated, many actually poor decisions are viewed as good ones when no accidents happen. The fact is that decisions that seem good at the point of making them may not lead to good outcomes and vice versa.

The rest of the paper is organized as follows. In Section 2, the research process is described, followed by review, definitions and proposition in Section 3. Section 4 presents the analysis of information needs for decision-making processes. Possible information related conditions which may lead to mistakes are also described. Categories of risk information are summarized. A simple case study is presented to illustrate the differences in information needs also. The results are discussed in Section 5, and conclusions are in Section 6.

2. Research process

The objective of this paper is to identify information needs for risk-related decisions, considering varied decision-making process and decision problems. The research process is illustrated by Fig. 1, where bold texts highlight the research activities and the location they are described in the article and the rest of the texts are the main outputs. The shaded box is mainly a literature review.

3. Review, definitions, and proposition

3.1. Risk-related decisions

In this study, we define risk-related decisions as decisions that will influence the major accident risk for a sociotechnical system, either by decreasing or increasing the risk. They can be decisions that introduce hazards, release hazards, influence the function of barriers (Liu, 2020), impact on the occurrence probability of undesired events, mitigate undesired consequences, etc. Included in the definition are also decisions that influence risk “indirectly”, such as decisions on maintenance budgets for safety equipment, manning levels for positions that manage and/or control risk, inspection and maintenance planning, etc.

It can be assumed that very few decisions are made with the intention to cause an accident, but decisions may influence risk without awareness. Normally, decision-makers try their best to maximize the benefits with respect to all objectives that they are aiming to fulfill, such as cost, scheduling, environmental performance and safety (Bofinger et al., 2015) and within the limitations in regard to time, resources, etc. It is difficult for decision-makers to measure and judge all concerns on the same scale or to have direct and correct perception of the risk of major accidents (Keeney and Raiffa, 1993; Merrick, 2011).

Some classifications of risk-related decisions have been given by Rosness (2009), The UK Oil and Gas Industry Association (2014), Bofinger et al. (2015) and Yang and Haugen (2015). Risk-related decisions vary significantly with regards to system diversity, product life cycle, accident prevention and consequence mitigation, their impacts on risk, targeted object and time span, existing knowledge and decision-making behavior etc. Even considering the same decision, the outcome could be affected by the available resources, the experience and knowledge of the decision-maker, whether there is one or more decision-makers and the perceived importance of the decision. The vast diversity in decision properties and associated contextual factors, makes it difficult to use single risk information that could meet all demands.

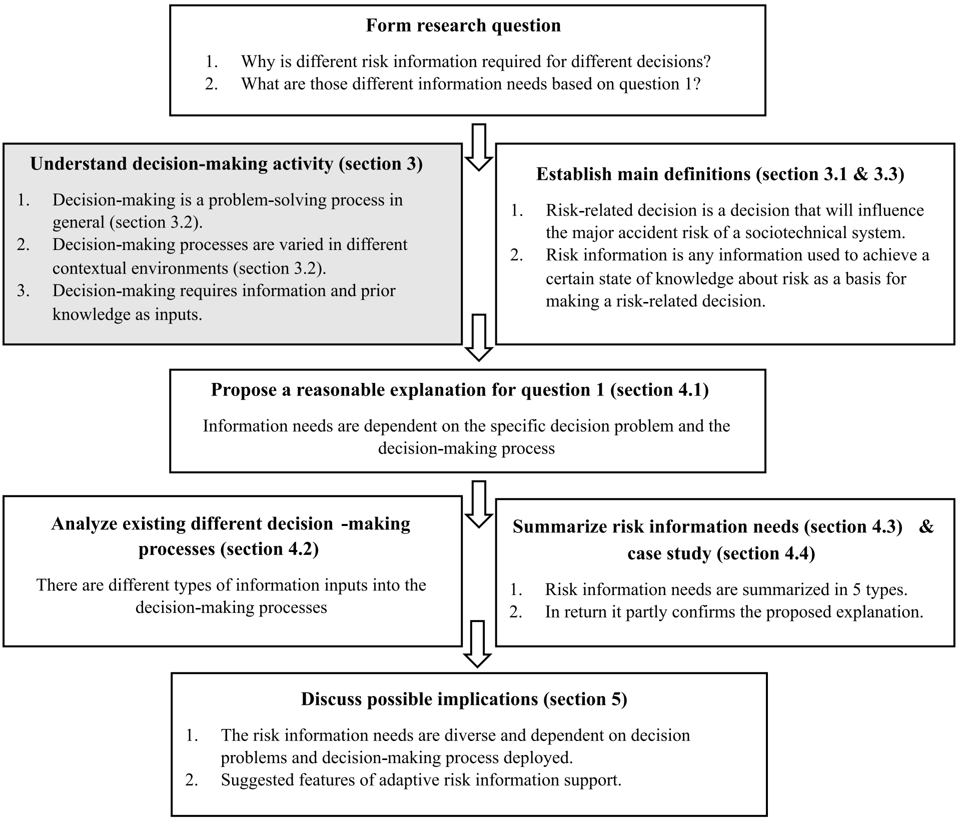

Fig. 1. Research process with activities and main outputs.

3.2. How are decisions made?

Many decision-making theories are developed for better understanding of how decision-makers make or should make decisions (Sullivan, 2009). In this paper, we adopt the opinion that decision-making follows a process from problem to solution, as shown in Fig. 2. Judgment, thinking, trade-off, making sense and reasoning are in this process. Prediction or projection is a key activity in decision-making. The existing decision-making theories and decision-making processes to a large extent show how risk-related decisions are made in different contextual environments.

There are 5 major groups of decision-making processes: bounded rational decision-making, rule-based decision-making, recognition-primed decision-making, sensemaking, and intuition. In a bounded rational decision-making process (March, 1994, 1996), decision-makers strategize and generate multiple alternatives and seek for the optimal choice or decision. Risk-informed decision-making is often studied based on the assumption of bounded rational decision-making theory (Aven, Vinnem and Wiencke, 2007; Haugen and Edwin, 2017; Zio and Pedroni, 2012).

Rule-based decision-making assumes that decision-makers know their situation by matching identities and rules and interpreting the implications of those matches. Decisions are predicated on the identity meanings that are established prior to taking actions (March, 1994, 1996). The identity meanings are usually associated with the general and self-recognized responsibilities and obligations in the organization. For example, the responsibilities and obligations for CEO, manager and front-line operators are different in risk management and accident prevention, and so are the rules they follow and the actions they take based on rule-following.

Naturalistic decision-making theories emerge in understanding how humans make decisions in certain circumstances, for example, how experts (surgeon, pilot etc.) make decisions under time pressure or in stressful situations. Under time pressure, it is more efficient to recognize patterns than to compare multiple alternatives to achieve the optimal outcome. The recognition-primed decision (RPD) model has been

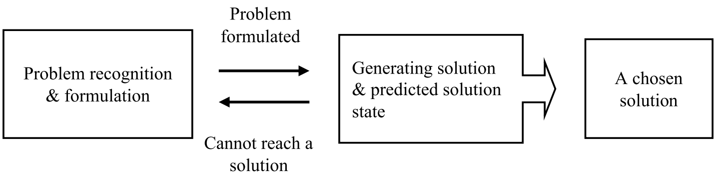

Fig. 2. Generic decision-making process from problem recognition to solution.

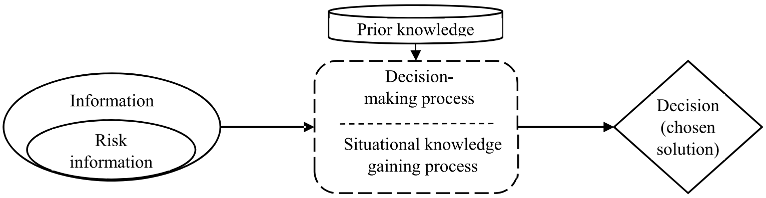

Fig. 3. Risk information, knowledge, and decision-making.

proposed from tracking the execution process of fire fighters and fire commanders (Klein, 1998). According to this model, decision-makers use prior experiences to recognize patterns and identify a single workable solution. Mental simulation might be used to see whether the solution works and determine the course of action. Situation awareness in dynamic decision-making also contributes to describe decision-making behaviors in operations of man-made systems (Endsley, 1995, 2015). Sensemaking (Bofinger et al., 2015; Choo, 2002; Klein et al., 2006a,b; Malakis and Kontogiannis, 2013; Richters et al., 2016) and intuition (Dane and Pratt, 2007; Hogarth, 2010; Kahneman, 2011; Kahneman and Klein, 2009; Salas et al., 2010) are also extensively discussed in the study of decision-making.

A mixed approach is also used in practices. For example, intuition and deliberate reasoning are combined to identify a problem or an alternative (Evans, 2010). Sensemaking is also used in problem formulation in the bounded rational decision-making process (Roth et al., 2010). In addition, Orasanu (1995) specifies a two-phase decision process model of situation assessment and response selection; pattern-matching, rule-following and comparing alternatives are the responses for selection in the two-phase model. Greitzer, Podmore, Robinson, and Ey (2010) proposed a combination model of situation awareness and mental simulation for guiding grid operator's decision-making.

In general, important factors that influence which decision-making process is applied when a decision problem occurs include:

- The decision-makers' knowledge related to the decision problem, including how much knowledge the decision-makers have and the degree of belief in the knowledge.
- Complexity and predictability of the system behavior (Snowden and Boone, 2007).
- Criticality of the problem.
- External constraints such as available time to make the decision (state of emergency) and available information sources.
- Number of decision-makers (whether there is one or several persons involved in the decision).
- Rules and norms for decision-making in the organization, such as NASA has its own risk informed decision-making procedure (Dezfuli et al., 2010).

For example, higher criticality of a decision problem will direct the decision-maker's attention to adopt a more holistic strategy, like a bounded rational decision-making process. More attention and resources in information collection will therefore be allocated. On the other hand, external constraints such as time pressure and limitation of available information will encourage an intuition-based decision-making process where less time and effort are required.

3.3. *Risk information for decision-making*

Provision of risk information for decision support has been a topic in areas such as risk-informed decision-making (ABS Consulting, 2001; Bofinger et al., 2015; Dezfuli et al., 2010; Office for Nuclear Regulation (ONR), 2017; The UK Oil and Gas Industry Association, 2014), operational risk analysis (Haugen and Edwin, 2017; Kongsvik et al., 2015; Sarshar and Haugen, 2018; Sarshar et al., 2018; Yang and Haugen, 2016), human-machine interface design (Abbott, 1990; Endsley, 2012 ; Rasmussen, 1983), severe accident monitoring and diagnosis (Allalou et al., 2016; Kim et al., 2015; Park and Ahn, 2010) etc. However, the majority of these studies focus on the best way of presenting risk using quantitative metrics, especially output from risk analysis, such as probability, consequences, expected utility, risk matrix. The underlying assumption is that risk information is quantitative measurements of risk that we get from risk analysis. The function of risk information is for detecting problems or presenting attributes of different alternatives, even though it may not be explicitly specified by the researchers. This utility is commonly stated as to increase risk awareness. A few studies of risk (safety) information needs has been conducted in public risk communication (Griffin et al., 2004; Huurne and Gutteling, 2008; Terpstra et al., 2014; Wiedemann et al., 1991) and risk (safety) management within the organization (Beck and Feldman, 1983; Nwagwu and Igwe, 2015; Sarshar et al., 2018).

The focus of this paper is risk information, and it is useful to distinguish between "information" and "knowledge". A good way of distinguishing is the statement by Machlup and Mansfield (1983); "information is acquired by being told, whereas knowledge can be acquired by thinking". Knowledge is information that have been sifted, organized, and understood by a human brain (Case, 2012). Information implies transfer, while knowledge is a state ("knowing"). We can create new knowledge without taking in new information from the external environment. In this paper, the definition of knowledge is adopted as "a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information" (Davenport and Prusak, 1998). In decision-making, information and prior knowledge of the decision-makers are the inputs and a chosen solution is the output, as illustrated in Fig. 3. Here, the decision-making process is also a situational knowledge gaining process because the knowledge of decision-makers changes from initial state to a new state with information acquisition. Situational knowledge means all forms of knowledge about a particular event or practice. Therefore, the study of information need is also a study of situational knowledge requirement.

In this paper, we define risk information as any information that is used to achieve an improved state of knowledge about risk as a basis for making a risk-related decision. Such a definition is much wider than plain risk numbers or risk matrixes or other direct expressions of risk. Risk information should be able to describe the real situation and be understood by decision-makers in communications. Risk information can be distributed across the physical, digital and social environment. Risk information includes at least the following categories:

- Direct expressions of risk, including risk measurements, expected values, probability distributions, consequences, hazardous scenarios, risk indicators, qualitative descriptions.
- Indirect expression of risk, for example, factors which influence risk, stop criteria, constraints, distance to the stop criteria and constraints.
- Information about how risk is interpreted and estimated, including the input data, assumptions and the process.
- Information that represent the validation, limitation and accuracy of the information mentioned above. This category expresses the uncertainty of the information, also named as meta-information.

4. Framework for information needs in risk-related decision-making

4.1. Two dimensions influencing information needs

It is reasonable to assume that two dimensions of factors influence the information needs in decision-making: the problem dimension and the decision-making process dimension, as illustrated in Fig. 4. More specific factors can be identified in these two dimensions: 1) identity (tasks and job responsibilities), 2) changes of problem due to development of situation, or decision-maker's definition of risk and values, 3) feature of problems (complex, poor-structured, unclear instructions, frequency), 4) knowledge (bias, experience improving or skill degradation, training, awareness), 5) environmental factors (attention, distraction, time constraints, organization's information environment, established interaction patterns). Fig. 4 is a simple and conceptual representation for the analytical purpose, while in reality these factors can be interlinked in some degree. For example, a certain task may have some specific features (whether it is complex, etc.) and the environmental factors (time constraints, distractions, etc.). In addition, some problems may demand a certain type of decision-making process.

The problem dimension deals with the exact decision issue that the decision-maker tries to resolve. A problem is formed as a gap between the true state and desired states (Jonassen, 2000), e.g. a deviation from a norm, standard, or objectives. Concerning all relevant decision-makers (who are the relevant controllers of risk), their problems are defined as the gap between their production objectives, safety objectives and other objectives, and the actual state of the system, see Fig. 5 for illustration. In the figure, we use the size of the circle to indicate the number of states. The true state is represented by a small circle, while there may be many desired future states (a large circle). The whole problem space consists of objectives related to the decision issue, background, and circumstances of the problem, which activity or system function & component or interaction or work procedure. In this regard, a decision-making process presents the way that the decision-maker engages in. Such a process can be analyzed to evaluate the information needs at each stage of the process for reaching the correct state of knowledge required. For example, Jenkins et al. (2017) use the decision ladder (Rasmussen, 1986) to elicit information requirements to support interface design of radiotherapy.

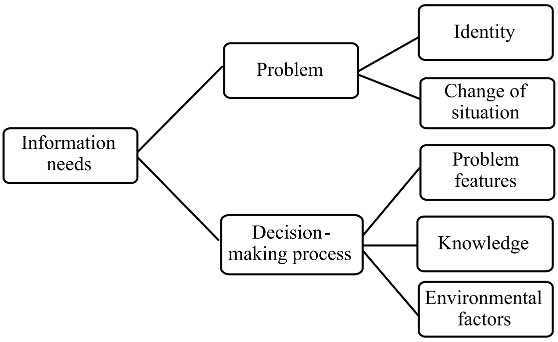

Fig. 4. Two dimensions for identifying information needs.

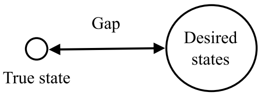

Fig. 5. Illustration of problem definition.

In this paper, only decision-making processes are studied for information needs. Different decision-making processes are analyzed in the next section to understand their information requirements.

4.2. Information needs for different decision-making processes

4.2.1. Bounded rational decision-making process

When a decision-maker is facing a critical and complex decision with little knowledge, the rational decision-making process is likely to be engaged. This process requires much effort from the decision-maker in both information collection, reasoning and deliberation. What alternative will be chosen heavily relies on the predicted consequences of all proposed alternatives and preferences. The environment in pre-decisions and outputs from the implementation of decisions are included in the decision-making process (Harrison, 1996). Table 1 summarizes the proposed information elements that could be used a bounded rational decision-making process.

Table 1
Role of information in (bounded) rational decision-making process.

Process element	Information element required to support the process
Intelligence: Identifying and structuring the problem and defining the context of the problem	1) Information to identify and structure the problem. 2) Information about the context in which the problem has occurred.
Design: Searching for alternatives	Information needed to generate or infer alternatives for decision-making if alternatives are not defined already. If alternatives already exist, information about these alternatives is required.
Choice: Screening and evaluating	Information about preferences (values that are derived from objectives), attributes of each alternative, suitable decision rules.
Monitor	Feedback information about outputs from the implementation of the decision.

Table 2
Information element in rule-based decision-making process.

Process element	Information element required to support the process
Situation	Cues which characterize the situation which is stated as the "if-conditions" in the existing rule.
Identity	Information about responsibility, positions of the decision-maker to judge the obligations and diagnose rules.
Rule	Information about existing rules which apply to the identity in such a situation.

4.2.2. Rule-based decision-making process

Rules are commonly applied as safety controls to constrain individual and organizational behaviors. In a rule-based decision-making process as a logic of appropriateness, the decision-maker needs to recognize the scenario for which rules exist (Rasmussen, 1983). Three questions need to be answered (March, 1994); 1. the question of recognition: what kind of situation is this? 2. The question of identity: What kind of person am I? Or what kind of organization is this? 3. The question of rules: What does a person such as I, or an organization such as this, do in a situation such as this?" The goal of the process is to establish identities and to match rules to situations. The rules may be formal, as in procedures or operation instructions, but may also be informal and rooted in culture, such as norms and established practices. Applying rules is a proper way to constrain behavior if there is high predictability in the system or severe consequence of misconducting. In new and emergent areas, there may not be enough time or experience to form good practice and therefore form rules. Table 2 summarizes the proposed information elements that is required in a rule-based decision-making process.

There are many causes of mistakes in rule-based decision-making, even though rule violation is not necessarily equivalent to decision failure (Reason et al., 1998). The following situations could be considered relevant to information deficiency: 1) not knowing the rule exists, especially for new employees, cross-organization supervision, 2) not informed of change in rule, 3) not clear or ambiguous instructions and texts, 4) incorrect perception of the situation by the decision-maker, 5) conflicting rules (multi-rules) exist for the situation, and 6) not evoking the right identity in the situation, e.g. the appointed on-site emergency team do not realize that they have to respond.

4.2.3. Recognition-primed decision-making process

The recognition-primed decision (RPD) model, as shown in Fig. 6, is proposed by Klein (1993a) to describe how experienced (skilled) decision-makers make sound decisions under time pressure. They do not compare different options but do pattern matching, mental simulation of the action course to find a solution that works and then implement the first workable solution. This represents a different kind of problem-solving strategy that demands specialized training where real-time, high-pressure decisions must be made. Their rich experience and knowledge let them "understand what types of goals make sense (so the priorities are set), which cues are important (so there is not an overload of information), what to expect next (so they can prepare themselves and notice surprises), and typical ways of responding in a given situation". And "the decision-makers do not start with the goals or expectancies and figure out the nature of situation" (Klein, 1993a, 2008). Table 3 summarizes the information elements required to support an RPD process.

Mistakes happen in experienced, knowledge-based decisions, where memory may be wrong during cue recognition and mental simulation, or just due to lack of confidence (Klein, 1993b). In this case, to ensure the right decision in those critical situations, situation shaping cues and information about constraints of action should be provided. In addition, information that confirms the situational knowledge will be helpful. Action course generated from decision support aids that represent the dynamic physical situation can reduce imagination errors during mental simulation. Rapid feedback information from operator's action can enforce learning and pattern recognition in the future.

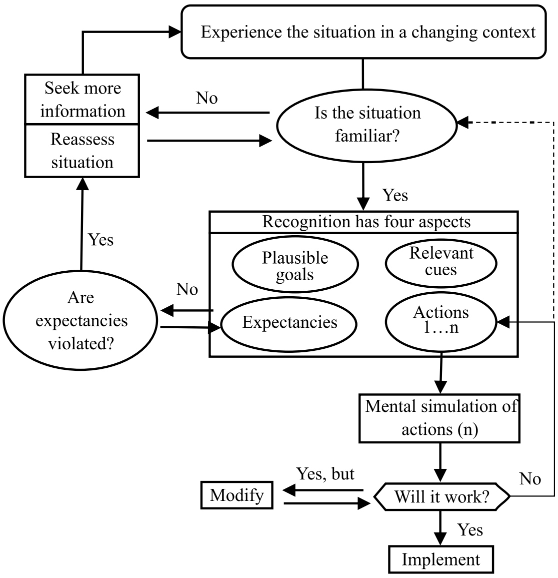

Fig. 6. Recognition primed decision-making process (Klein, 1993a).

Table 3
Information elements in the RPD model.

Process element	Information element required to support the process
Situation recognition	Cues, plausible goal, expectancies, actions which characterizing the situation or pattern which is familiar to the decision maker.
Mental simulation	Mental models from memory that present the course of action and corresponding consequences of the action (whether the action will work to achieve the goals). Constraints that limit action course.
Action modification (occasional)	Information about the physical situation.
Action judgment	Confirmation that the action will work.

4.2.4. Sensemaking in decision-making process

The definition of sensemaking is adopted as "a motivated, continuous effort to understand connections (which can be among people, places, and events) in order to anticipate their trajectories and act effectively" (Klein et al., 2006a). There are other interpretations of sensemaking, from generic definitions to specific application fields (Chater and Loewenstein, 2016; Linderman et al., 2015; Sandberg and Tsoukas, 2015; Weick, 1995). Sensemaking is the deliberate effort to understand events and begins when someone experiences a surprise or perceives an inadequacy in the existing frame (process-driven) and the existing perception of relevant information (information-driven) (Klein et al., 2007). Sensemaking needs cues as triggers, such as surprises that can be interpreted as a lack of preparation, vigilance, control, or discipline in an organization. The cues can be issues, events, or situations

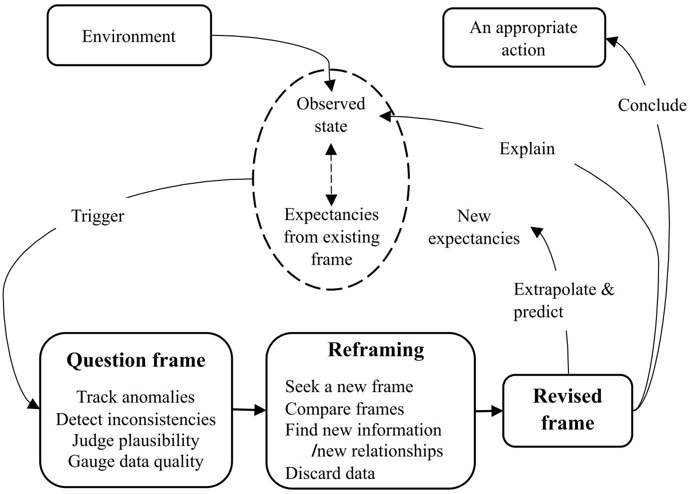

Fig. 7. Modified sensemaking process from Klein et al. (2007).

with ambiguous meanings and/or uncertainties. Examples are applying new technologies during operation, changes of rules or operation instructions, and other changes that create dynamic and less predictable environment where existing frameworks for solving problems repeatedly and maintaining safety do not work (Maitlis and Christianson, 2014). Unexpected events do not necessarily trigger sensemaking, which only occurs when the discrepancy between the expected state and observed state is large enough, and important enough, to cause individuals or groups to ask what is going on and what they should do next. Actions to find more information for explanation might be part of sensemaking. For example, astronauts react to a crisis situation by trying to make sense of the situation by making checks and running through procedures carefully and systematically to see whether they could establish what had happened (Stein, 2004). Klein et al. (2007) present a data/frame model of sensemaking which describe sensemaking as the process of fitting data into a frame and fitting a frame around data to explain prior events and anticipate future events. Certainly, the accumulation and enrichment of information is part of sensemaking – the synthesis of data into higher-order inference. The sensemaking process is shown in Fig. 7.

The process of sensemaking requires:

1) Information which triggers the process;
2) Information (cues) which indicates and confirms plausible explanations.

Sensemaking is retrospective, decision-makers build up their own story/frame in a cyclic and iterative manner to assemble the information they received. Sensemaking depends on the interaction between people, situation, and knowledge (Klein et al., 2006a). Those characteristics of sensemaking are relevant to information support. For where sensemaking is required, the system should be designed to be flexible and allow information searching, action and exploration in it. Errors of sensemaking occurs when the wrong frame is adapted. For example, when decisions are made in a narrow frame which makes the solution seem satisfactory or most beneficial while it ignores some important but not easily visible consquences. Such occurrences may be due to several reasons: 1) not enough knowledge to interpret information and identify new frame, 2) important cues have not been observed or recognized, and 3) information indicates several possible frames and competes for plausibility.

4.2.5. *Intuitional decision-making process*

Intuition is one of human's basic cognitive activities and it goes on unconsciously. A definition of intuition is that "they knew without knowing how they knew" (Kahneman, 2011). Decision-making relying on intuition is fast and effective. In real life, intuition is extensively applied (Dane and Pratt, 2007; Khatri and Ng, 2000). In the decision-making process, intuition can have two functions. First, intuition serves as input to deliberative processes. For example, in highly regular environments, decision-makers can use intuition to sense the irregularities. Second, when facing a regular decision task, decision-makers can intuitively generate a workable solution automatically (Çizgen and Ulusu Uraz, 2019; Rasmussen, 1983). Intuition seems similar to pattern-matching in recognition-primed decision-making model, but it is not the same thing because pattern-matching is a conscious activity.

It is necessary to differentiate immature (general) intuition and educated (expertise-based) intuition with regards to the accuracy (Salas et al., 2010). Expertise-based intuition is where the decision-makers have developed a deep and rich knowledge base from extensive domain experience (Salas et al., 2010), therefore can be accurate. As clarified by Hogarth (2010), errors in intuitive thought are essentially 1) those of bias induced from past experience (e.g., using an inappropriate anchor in judgment) or 2) personal transient impacts from emotions and salience of some information. Expertise-based intuition is likely to be relevant to use in regular decisions in predictable system environments but not valid for emergent situations. It takes time to develop intuition, which means that it is not possible for decision-makers when facing an unfamiliar, unpracticed condition or issue (Kahneman, 2011; Kahneman and Klein, 2009). To maintain and make use of expertise-based intuition, information inputs from the system and its environment should be regular and directly sensible even without attention or conscious awareness. The same information items as experienced or learned in the past should be present.

4.3. *Types of risk information needed for risk-related decisions*

By considering the information needs of the various decision-making processes in the previous section, we can conclude that the needs for risk information in decision-making can be classified into types listed below. Each type represents a specific function and content of risk information in decision-making.

Type 1: information reflecting potential existence of safety problems for problem detection and identification. Such information can be a direct expression of the safety problem or an indirect expression but sufficient for the decision-makers' inference of the problem, such as results from risk evaluation showing a gap between risk analysis output and risk acceptance criteria. Examples of direct expression are a) the estimated worst consequence is unacceptable, b) the estimated probability of explosion during the mining operation is far higher than the acceptable criterion, or c) the plane is likely to crash before it reaches the planned destination. Examples of indirect expression from scenario parameters, are a) the altitude deviation from terrain is very close to the separation threshold, or b) fuel quantity may not be sufficient to reach the planned destination for the flight. In addition, it also includes information which forms the if-conditions of a certain rule in rule-based decision-making process. For example, considering an existing procedure: "Shut down the process if process parameters a, b, or c are exceeded. In such a situation, information about the process parameters a, b, and c is critical for the decision-maker to judge whether to take the specified action in accordance with the rule.

Type 1 information is not necessarily a simple number. It could be a set of situation features and safety value and objectives which formulate the problem. It would be impossible to detect a safety problem without considering safety as valuable, such as the mistake in Challenger lunch decision (Vaughan, 1996).

Type 2: information of contextual factors. This could be e.g. information about the severity and urgency to make the decision. This information helps the decision-maker evaluate the relative importance of the decision problem compared to other tasks at hand and judge how much effort should be put into resolving the decision problem and how fast the action should be implemented.

Type 3: information about constraints, system boundaries, specifications, and requirements of workable solution. Examples are operating limits, critical operating parameters, safety margins, guidelines, availability of required resources and cause-effect relationships. This group of information is used to generate solutions in the bounded rational decision-making process and mental simulation in the RPD process. Type 3 information can be classified into three subtypes according to their functions.

Subtype 3.1: safety margins and operating limits. Typical examples are 1) minimum operational level of redundancy of safety-critical equipment must have at least three of five pumps operating or available and 2) the distance between two cars on the highway should be at least 100m if the speed is greater than 100 km/h.

Subtype 3.2: information about requirements for workable solutions and availability of required resources, such as money, time, space, a special skill, or a certain system/subsystem condition that is required for an action to be feasible.

Subtype 3.3: cause-effect relationship between a proposed solution and possible outcomes, such as "sand can be used to cover chemical substances" therefore "sand can separate chemical and air" therefore "sand can be used to extinguish chemical fire". There is a strong causal link between the proposed solutions and possible outcomes. This information is important for generating a solution to achieve the desired objectives.

Type 4: attributes or features of alternatives for comparing and evaluating. A decision-maker needs to make a judgement based on Type 4 information on which alternative is going to achieve the maximum benefits. Typical examples are decrease/increase of risk or probability of introducing hazards/undesired events of the alternative sets.

Type 5: rules that are set to maintain safety or control risk, such as procedures, rules, and standards. These rules have a function of guiding actions under certain circumstances for certain identities in the organization. It has been accepted that some professionals set their own situation-specific rules. In this kind of circumstances, information about the rule does not need to be supplied. However, there are rules which are set by others such as designers, managers or others according to previous experiences or accidents. Those rules need to be clearly communicated and reminded when situations, where the rule applies to, show up.

4.4. *Case study for illustration*

In this part, we use the handling of iceberg threat to an offshore installation as a case to illustrate the differences in information needs when different decision-making processes are deployed. We consider several similar scenarios related to the handling of iceberg threat and avoid serious collision between iceberg and FPSO (Floating Production Storage and Offloading unit). The basic scenario is that an FPSO is in production during the season when iceberg collision may occur. The offshore installation manager (OIM) is the one in charge of handling situation where an iceberg threatens the FPSO. The relevant objectives of the OIM is to keep the FPSO in operation and to keep it safe (no serious damage from collision).

4.4.1. *Scenario A (sensemaking)*

Iceberg season is coming. So far there is no visible iceberg coming toward the installation. However, another FPSO in the same area suddenly sails away. The OIM hears about this (abnormal observed from the environment) and wonders why this is happening. FPSO sails away only on few occasions and something serious might be happening. There may be several reasons for moving off location. One possibility is to avoid severe environmental conditions/loads. Another one is being taken off location for dry-docking, repair, or maintenance work. Then the OIM possibly starts to search for relevant news and make some calls to those who possibly know what is happening. At the same time, the manager gets informed that some big icebergs are coming towards the field (additional information to confirm the hypothesis) and realizes that very likely the other FPSO is moved off from the location to avoid iceberg collision and disconnection is necessary to avoid iceberg collision for the FPSO of which he is in charge (confirms the threat and chooses corresponding strategy to handle it).

4.4.2. *Scenario B (bounded rational)*

An iceberg is detected by radar. The iceberg can damage the hull structure and positioning system if a collision occurs. The forecasted drift Closest Point of Approach (CPA) is about 0.4 NM from the FPSO and Time to Closest Point of Approach (TCPA) is 4–9 h. There are several ways to handle icebergs: 1) disconnect the FPSO and sail away, 2) change the direction of iceberg by towing or use of water cannon, 3) fragment iceberg by explosive techniques such as shooting or implanting slow-burning explosives Thermite, 4) closely monitoring the iceberg to get a more accurate assessment of the threat including load dynamics and trajectory prediction; if the iceberg is not threatening the FPSO, then it can be ignored; if the iceberg is threatening, then disconnection should be conducted. The costs, requirements, constraints, and success chance of each solution should be considered when deciding which one to choose. After a thoroughly deliberation, the OIM concludes that option 4) is the best.

4.4.3. *Scenario C (rule-based)*

A detailed procedure has been made to guide how to handle this problem. A zone-based guideline has been provided in the ice management procedure. Different response actions are given based on the FPSO serviceability criteria related to iceberg size and significant wave height, zone of the iceberg and forecasted drift CPA. The manager finds this procedure and compares current iceberg situation (threat level of the iceberg, location of the iceberg, and zone location of the forecasted drift CPA of the iceberg) with the requirements in the procedure. The comparison indicates that the FPSO should be disconnected at the current stage. The OIM decides to disconnect the FPSO and sail away.

4.4.4. *Scenario D (recognition-primed)*

Iceberg season is coming again. The OIM has experienced such ice season for many years and has had formed a series of strategy. First, she/

Table 4
Information required for the four scenarios about iceberg handling.

Scenario	Information
A (sensemaking)	1. Information about another FPSO is disconnected and sailed away. 2. Information about severe iceberg presence.
B (bounded rational)	1. Information about the iceberg presence. 2. Information about collision risk prediction of the iceberg, including the potential consequences of collision, the likelihood of collision, the range CPA and range of TCPA. 3. Information regarding the costs, requirements, constraints, and overall successful chance of each solution. 4. Information about the algorithm to determine which one is the best.
C (rule-based)	1. Information about iceberg presence 2. Iceberg handling procedure. 3. Current condition of the iceberg corresponding to the procedure statement, including threat level of the iceberg, location of the iceberg, and zone location of the forecasted drift CPA of the iceberg.
D (recognition-primed)	1. Information about iceberg presence 2. Information of the size of the iceberg, distance from the FPSO, estimated CPA and TCPA. 3. Information about specific requirements and environmental constraints for chosen solutions. Such as: time and tools required, weather conditions to conduct towing successfully.

he monitors the iceberg movement closely and get an accurate estimation of the threat and determine what to do next. If the iceberg size is medium, towing and cannon shooting would be applied to change the direction. If there are many icebergs and the sizes of some icebergs are not easy to estimate, the manager will order to disconnect the FPSO and sail away, etc. In this case, a series of patterns and corresponding measures have been established. When a medium size iceberg is detected close to the FPSO, the estimated Closest Point of Contact is less than 0.1 NM, and Time to reach the Closest Point of Contact is 2–2.5 h. The manager decides to tow the iceberg first which is often the most used iceberg handling technique. However, the time required to establish a successful towing is 4 h. The available time is not enough to conduct a tow; eventually, the manager decides to disconnect the FPSO (which requires about 40 min).

Comparing the four scenarios above, we can see that sensemaking happens in an unclear environment so that the decision-maker needs to collect information and form her/his own judgment about what is happening and take actions based on the causes of the scenario. While for the other three scenarios, there are clear signals about the problem. In the process of bounded-rational decision-making, the decision-maker needs to spend quite much time to collect information compare different known solutions and find out the best in terms of safety and operational limits and cost. In the opposite, rule-following is much simpler. When it comes to recognition-primed decision-making process, much experience and knowledge is required about when should do what and how. For sensemaking, good information collection is required for the decision-maker to find out what is truly happening combining prior knowledge. For rule-following, information is required to know the match of current condition and demanded condition in the rule. For recognition-primed decision-making process, the decision-maker relies on the signals she/he gets and environment constraints for chosen solution to judge whether the chosen solution will be successful or not. Therefore, we can conclude that which decision-making process will be applied is context-based, and information needs will be different, as showed in Table 4. However, information available to the decision-maker might also change the decision-making process. For example, if the decision-maker finds out that there is a rule regarding iceberg handling which should be followed and the real iceberg threat, then the other three theoretical processes might not occur either.

5. Discussion

In this section, we want to expand a bit our observations and insights further on 1) decision-making process, 2) information for uncertainty reduction in decision-making, and 3) possible implementations in decision support.

5.1. Decision-making process

Any process has its own background, specific environment, and requirements to lead to a good decision. For example, if a procedure or norm exists for specific types of decisions in the organization, using work permit approval or action approval as an example, the information support system should be designed to ensure the required information elements are effectively supplied. The diversity of information needs is part of the fact. Therefore, risk information categories summarized in this paper are not necessarily required in every case of risk-related decision-making.

As mentioned earlier, predictability and state of knowledge, criticality and external constraints influence the decision-making strategy that a decision-maker may deploy. From the analysis of decision-making processes, we can see that the higher the predictability of the system behavior, the simpler, more efficient decision-making processes can be applied to achieve the same decision quality. Predictability is influenced by several system properties including complexity, inherent uncertainty of system behavior and available knowledge about the system. When it comes to external constraints including available time, accuracy and availability of risk analysis methods, information sources etc., the shorter time available, the more efficient process will be engaged. When available information resources are limited, general intuition might be applied. However, the less prior knowledge the decision-makers have about the situation, more deliberate effort will be put into it and there will be a higher demand for information. In addition, it is obvious that the bounded rational decision-making process is not constrained by working memory as much as RPD or sensemaking. The capacity limitation of working memory implies that certain information-mapping tools might be needed for RPD or sensemaking for resolving complicated issues.

There are two basic predictions required across the entire decision-making process. The first is the prediction of what is going to happen if no action is taken. This is part of the problem formulation and is what many risk analyses do in risk management and online accident diagnosis and prognosis (Ahn and Park, 2009; Allalou et al., 2016). In order to formulate a problem, safety objectives must be well understood (Merrick et al., 2005) and a safety criterion must be established (can also be called boundary or constraints) (Merrick, 2011). The second prediction is what will happen, conditional on alternative courses of action.

However, decision-makers do not necessarily explicitly conduct these two predictions. The common definition of "choice-based" bounded rational decision-making focus on the second prediction. Situation awareness emphasize the first prediction about what is going to happen based on the current situation (what is going on right now). Mental simulation in RPD use imagination to predict whether the course of action will work. Moreover, sensemaking is about using actions, checking and reasoning to test out connections in order to project and act further. As for the rule-based decision-making process, the two predictions were made when setting up the rule. Therefore, decision-makers who follow the rule do not need to make any extra effort to make predictions.

Another important prediction is the objective prediction because it directs changes in the problem. The objective might change when time goes, or the risk perception changes. This is more critical when it comes to long-term (across years) decisions than short-term ones. This is applicable to the case when production objectives are overrated in early phases of projects while later, risk is of more concern. An earlier problem may be not a problem anymore or the other way around because of changes of objectives. In organizations, objectives need to be communicated as information, so does the change of objectives.

In real organizational decision-making, sensemaking may be part of normal decision-making activities in daily operation in situations where decision-makers reactively respond to unfamiliar system changes, external disruptions, malfunctions etc., for example, the decision-making process in emergency and crisis handling (Baber and McMaster, 2016; Kefalidou et al., 2018; Richters et al., 2016). Therefore, facing rapidly changing technology and society, sensemaking is likely to be an important element in decision-making for risk management, because sensemaking provide a way of handling uncertain environments which is inherent to the circumstances of risk-related issues. The design of sociotechnical systems should support efficient and accurate sensemaking towards the establishment of resilient systems.

5.2. *Information to reduce uncertainties in the decision-making process*

Uncertainty that is understood as limited knowledge is often discussed in decision-making (Apostolakis, 1990; Aven and Reniers, 2013; Lipshitz and Strauss, 1997). Knowledge increases when more information is taken in and perceived through the whole decision-making process, as explicit knowledge is likely to be elicited from information in a very short time. The perception of uncertainty will also trigger active information seeking. The requisition of information in turn reduces the uncertainty (increase the amount of relevant knowledge and increase the belief of the knowledge) of the decision-maker. We can assume if knowledge (what the decision-maker already knows) is not enough for a sound decision, then extra information is required and should be supplied by the organization or system. Therefore, we may need to differentiate what information we need to retrieve from outside and what we have. On the ther hand, uncertainty also affects our ability to interpret the received information and to make predictions about the future. In addition, what the decision-maker already know also matters. It directs the decision-maker's attention by relevance, links the decision-maker to a fact, and allows the decision-maker to take in new information from the environment (Nagel, 2014).

Information need is a knowledge gap between what is already known and what should be known. This means that there is a recognized anomaly in the user's state of knowledge concerning some topics or situations. The collection of information in all categories can reduce uncertainty, increase the robustness to handle remaining uncertainty, and increase the knowledge or confidence in knowledge. It is a continuous process by which information is interpreted at each step of the decision-making process. The proposed categories of information can be used to further explain how lack of information and uncertainty impact decision-making and lead to poor decisions. For future application, uncertainties of the required information in the decision-making process should be presented together with the information itself or lack of information. As for uncertainty reduction, at least four strategies can be applied: 1) searching for existing information, 2) confirming or discarding information by using other information sources, 3) using existing information to form new information by analogy or inference, 4) testing and interacting with the system environment to get new information.

Uncertainty reduction is a key process in decision-making because decision-making involves prediction in which uncertainty plays a large role. When it comes to predicting the future, we should not assume that we could have perfect information. However, it is easier to achieve a more accurate prediction when the time span of prediction is short and influencing variables are few. In order to get relatively more accurate risk estimations for different time horizons and system complexity levels, we need to choose the right risk analysis methods and carefully define the system under concern. The results of risk prediction will impact risk control actions, and again influence risk, back and forth. The loop of risk prediction and risk control action also demands simulation in risk estimation and control.

5.3. *Adaptive risk information support*

In any large organization, many decision-makers are involved in risk-related decisions in operation. However, those decision-makers face different risk-related decisions due to their distinct positions and responsibilities. The link between decision-makers from different levels are made by the objective hierarchy, shared values and preferences, and organizational structures. For example, outcomes of high-level strategic decisions will constrain lower level planning and execution decisions. Those constraints can be spatial, temporal, technical, resources or objective related. Planning decisions are commonly constrained optimization problems, which are to allocate the planned activities within the constraints. The information needs for these decisions will be different. Decision-makers will require different information when the decision they face changes and when their way of resolving the problem changes with increased experience and knowledge.

The most difficult part of information support is when contingent but critical situations show up, for example the Fukushima Daiichi nuclear disaster (The National Diet of Japan, 2013). Situations that indicate the occurrence of a major accident do not repeat often. Decision-makers do not have enough experience to conduct mental simulation correctly or to generate workable actions. Very likely, rules such as instructions will not exist. Sensemaking has a high potential in such situations. However, sensemaking is directed by plausibility and not necessary accuracy, which means that the perception can be wrong. Such may imply that we cannot rely on intuition, sensemaking, RPD or rules for decision-making about major accidents. Bounded rational decision-making process usually takes a long time, which may not be acceptable in emergency situations when a major accident is developing. The possible solutions can be 1) direct an accuracy guided sensemaking in decision support or 2) make a fast analytical tool to project the future and tell the operators the requirements of workable solutions (for example, how long time until the critical thresholds are exceeded) and this fast analytical tool must have been prepared and available all the time.

To manage the risk-related decision-making across different decision-makers in the organization, constructing an adaptive information supply system will be helpful. Such a system should have the following features:

1. It provides targeted risk information to specific decisions and decision-makers.
2. The supplied risk information first helps the decision-makers detect potential risk issues.
3. The supplied risk information not only fits the needs of the decision, but also supports the decision-makers' strategy for resolving the issue to ensure effective utility. This means it should meet the situational needs and match the experience and knowledge of the decision-makers. This can also reduce information overload and save time as every piece of information retrieval takes effort.
4. It provides warnings about mismatch of deployed decision-making process and decision-maker's knowledge base and resources, which are required by the decision-making process, to avoid decision failures.
5. It is able to provide physical accident causation models for the decision-makers to deduct inferences when they encounter unfamiliar situations or surprises to get a more accurate understanding of the development of the accident.
6. The supplied risk information changes when the risk-related decisions change.
7. It is able to give a rate about the importance of a risk-related problem (not necessary to quantitatively evaluate the importance, but more like scenario-oriented, qualitatively) for resource allocation such as attention and time because any person in the organization usually need to handle many tasks at the same time.
8. It provides feedback about the outcome of the decision for monitoring effectiveness and learning.

It may be difficult to achieve those features listed above (at least some of them). However, we think that the difficulty does not necessarily influence them working as principal design guidelines. Designers should strive to get as close as possible for the decision problems of concern. Information system for routinely responsive tasks is the easiest (Howard, Hulbert and Farley, 1975). Therefore, designers of information system can perhaps classify decisions into different categories and design varied functions for each of them.

The study of information needs is meaningful due to the very normal contextual factors that constrain our access to infinite information or infinite time to search for information or creating the proper knowledge. Even though decision-makers are actual information seekers, who is continuously looking for what is missing. When it comes to information acquisition, balancing the accuracy, cost and efficiency in information retrieval can be further discussed during implementation. We emphasize again that training is important to prepare knowledge that the decision-makers need (Orasanu, 1995). The better training, the more efficient strategies can be adopted for decision-making. In addition, sufficient information supply does not necessarily lead to good decisions. It also depends on the decision-maker's perception of the information.

6. Conclusion

There is a wide range of risk-related decisions across the whole operation period of any major socio-technical systemin the process industries. To provide targeted risk information to the distributed decision-makers and support an effective and efficient decision-making activity and eventually contribute to accident prevention, their decision tasks and way of making decisions should be analyzed and considered, especially when designing decision support tools.

In this work, we have proposed a definition of risk-related decisions that influence major accident risk in sociotechnical systems and a wider definition of risk information. Those definitions/terms could raise the attention and potentials in both academia and industry in managing risk-related decisions from the angle of information support and promote further research in this topic. By analyzing commonly applied decision-making processes for risk-related decisions, risk information is found to 1) detect and characterize risk-related decision problems, 2) indicate the severity and urgency of a decision, 3) state requirements of workable solutions and environment constraints to design solutions, 4) represent attributes that are used for comparing and evaluating alternatives or solutions, such as predicted possible consequences of the set of potential options, and 5) act as rules which are set to maintain safety or control risk. The actual function the risk information is dependent on the actual decision-making process. The information categories based on decision-making processes also put the decision issues in a structured manner and make the problem solvable. The framework of information needs proposed in this paper can facilitate future research that intend to ease the problem of information deficiency in decision-making by designing improved information system. Moreover, the study of information needs can further direct the risk information distribution to different decision-makers and related knowledge management in the organization and increase our understanding about how organizational factors contribute to the occurrence of accidents.

However, there is no detailed exploration of specific risk-related decisions in this paper. It would be interesting to investigate decisions in the perspective of accident prevention from the life cycle span of system development by employing a causation model (for example, by investigating decisions which shape risk influence factors) and responsibility distribution in the sociotechnical system. In addition, it is interesting to enhance the combined advantages of different decision-making processes, such as further exploring and facilitating accuracy guided sensemaking in handling contingent and safety-critical situations. The dependence on the knowledge of decision-makers also reminds us about the need to call for further research on the knowledge requirement of decision-making activities and further on how to enhance training for risk-related decision-making, such as 1) training which improves the causal-reasoning capability of decision-makers, 2) including accident causation models in the training material which give the operator predictive meaning of system parameters and cues (by training programs, learning from experience, storytelling).

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Article 2

Human factor challenges and possible solutions for the operation of highly autonomous ships

Tiantian Zhu, Stein Haugen and Yiliu Liu.

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Human factor challenges and possible solutions for the operation of highly autonomous ships

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At present, there is a strong drive towards development of autonomous ships and other marine systems. Some commercial, large size, long voyage, highly autonomous ships are under development and plan to operate in coming years. Many discussions exist about the human factors in autonomous ships because humans are expected to continue to play some roles in ship operations. However, the increased autonomy will challenge the performance of human operators. In this paper, we have identified issues impacting on operators' performance through the whole process from problem recognition, decision-making to action implementation. Those issues include, but are not limited to, level of autonomy design, remote operation, transition of operating modes, collaboration between crews and autonomy, teamwork between crews, goal and sub-goal omission, operation rules following, uncertainties, mental constraints and characteristics, and changes during operations. Those issues are integrated in a descriptive, holistic representation to illustrate the complication of human factor issues in the operation phase at the same time provides guidance to solutions. Both design-based solutions and operation-based solutions are identified in order to resolve the human factor challenges.

Keywords: autonomous ships, design, human factor in operation, solutions, uncertainty

1. Introduction

A ship is a complex system and the main function of water transportation is achieved by a combination of many subsystems (Rødseth et al. 2017). The degree of autonomy of a ship increases as more sub-functions become automated. The developments in dynamic positioning (DP) systems, collision avoidance systems, anti-grounding systems, and automatic berthing systems etc. provide the technical feasibility of highly autonomous ships. However, those autonomous functions increase the ship complexity compared with conventional ship. They rely heavily on data from sensors, sensor reliability and algorithms which may introduce new design errors (Ahvenjärvi 2016). In addition, the capabilities and reliability of those functions are still limited. The system may not be intelligent enough to handle all the situations, and it may fail. This challenge the ship reliability and even safety (Lützhöft et al. 2002), for example, some anomalies have been identified in Electronic Chart Display and Information System (ECDIS) (International Maritime Organization 2017), the DP system leaves little time for operator to intervene when it fails in unexpected ways (Hogenboom et al. 2018). Therefore, human operators must be equipped and be able to quickly understand the situation and act accordingly. Their reliability is very critical as the last barrier for safe operation at the sharp end.

In principle, at the higher degree of autonomy, the more decisions and actions will be made by computer-controlled systems rather than by humans. However, even though the amount of decisions and actions by human operators have reduced, the remained and added ones are critical and complicated. This provides chances and necessaries to analyze human factors issues from detailed cognition and behavior perspectives to discover problems and call for solutions in order to ensure the long-term safe operation of highly autonomous ships, which forms the objective of this study.

Group interviews (Man et al. 2014), scenario simulation focusing on situation awareness (Man et al. 2015), investigation of other industrial domains (Wahlström et al. 2015), analysis of possible human failure events in the voyage (Ramos et al. 2018b), and studies of possible Performance Influencing Factors (Ramos et al. 2018a) have been conducted to understand the possible human factor issues in the operation of highly autonomous ships. However, impacts from level of autonomy (LoA) design configuration (Endsley 1999) and crew/ system teamwork, operating mode transition etc. has not

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been addressed in those studies. However, these earlier studies have formed the basis for a holistic review of the issues with an emphasis on their impact on human operators' performance in problem recognition, decision making and action to accomplish their dedicated tasks. The discussion of those issues can provide further guidance not only in the design approach but also in technical solutions in cooperation with future operation contexts. Understanding the operation context is important before we go to human factor issues and solutions.

In this paper we distinguish degree of autonomy and level of autonomy. The degree of autonomy indicates how much automation is applied to the system functions (Nof 2009), while level of autonomy (LoA) determines interaction between operator and system autonomy for completing a specific decisive task (Sheridan et al. 1978). In addition, the terms "automation" and "autonomy" are used interchangeably.

2. Assumptions about operator involvement, tasks and context

Many concepts for autonomous ships are proposed, and we therefore need to define what is the basis for our study. The most common concepts is that the ship is controlled by autonomous controllers with human operator at the SCC monitoring it. A possible configuration of the SCC team is that it will consist of a supervisor, captains, engineers and operators. Each operator is required to monitor several unmanned vessels via a workstation according to MUNIN project (Man et al. 2015, MacKinnon et al. 2015). An alternative solution is with reduced crew on board. Exactly what tasks the crew will perform is in most cases not yet clear.

This will bring changes in 1) goals and tasks, 2) required resources (information, time, etc.) for tasks to achieve the designated goals 3) work environment, 4) ways of receiving information (display) and command. This will apply to the whole voyage, covering preparation, departure, maneuvering, in-voyage planning, and voyage termination.

The navigation tasks can be divided into operator Dynamic Navigation Task (DNT) and control system DNT (Rødseth et al. 2018). Operator DNT include at least: 1) Mission planning, designation and confirmation. 2) Handling critical scenarios during voyage (collision, grounding, etc.), including all aspects of avoidance and response. 3) Monitoring ship health and status, judging needs for maintenance and preparing maintenance plans. 4) Communication with other ships and shore. 5) Maneuvering the ship (remotely or onboard) in constrained waterways and in ports. 6) Learning from the performance and outcomes of ship operation to improve future interactions (gain experiences).

The complete voyage will take place at different levels of autonomy (Rødseth et al. 2017). For example, in open and calm seas, the navigation function of the ship is achieved by the autopilot function, while during departure and voyage termination, humans may need to remotely maneuver or supervise the ship. The appropriate degree of autonomy is thus situation-dependent and may change in a dynamically changing environment (Inagaki 2006, Rødseth et al. 2017), as illustrated in Figure 1. Accordingly, the interaction activity of the operator changes depending on the operation and the transition between them, as shown in Figure 2.

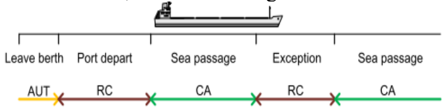

Fig. 1 one example of autonomous modes in ship voyage proposed by Rødseth et al. (2017) (AUT: remotely monitored and fully automatic, RC: direct remote control, CA: constrained autonomy)

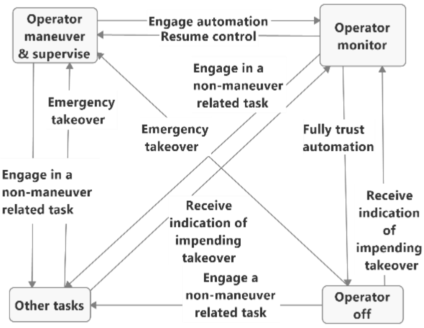

Fig. 2 Operator transition network

3. Human factor challenges

The performance of human operators essentially depends on three aspects: 1) problem recognition, 2) making timely and right decisions and 3) acting correctly and timely in accordance with the decision, continuously or on demand. However, issues in the working contexts for the dedicated operators' tasks like LoA design configuration, remote operation etc. pose challenges to the three aspects, as shown in Figure 3. A holistic way of looking at the impact of those issues is required, considering dependence on tasks, environment, system and human characteristics and their dependencies overtime.

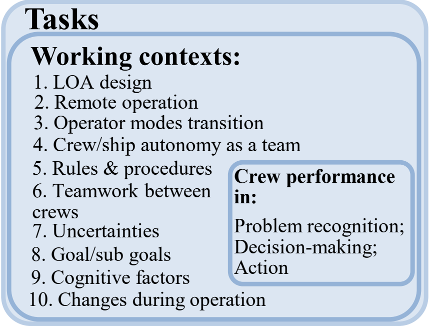

Fig. 3. Human factor related issues

3.1 LOA related issues

LoA significantly affects the operator's situation awareness and the way of interaction between human and automation (Johnson et al. 2018, Endsley 2018). The LoA design not only defines authority/responsibility allocation between those two agents, but also further guide information gathering, analysis and sharing between human operators and computer. Therefore, the LoA design decisions will influence the mental workload and its balance across time, human operator's situation awareness and eventually human performance. There are different advantages and weaknesses associated with each LoA. Manual control is desired during automation failure or when there is an indication that automation may fail. Intermediate LoAs maintain human in the loop and allow operators to adopt readily to automation/decision-aid errors and other situations with increased task load. Higher LoAs can relief workload/vigilance especially during complex tasks but lead to operators' "out-of-the-loop" unfamiliarity and cause skill degradation in long-term. This threats safety when system fails (Ruff et al. 2002).

3.2 Remote operation related issues

Reduced sense of ship due to remote operation has been identified as a main factor for human error (Wahlström et al. 2015, Man et al. 2015, Man et al. 2018, Ramos et al. 2018a). The MUNIN project examined several scenarios of ship handling from SCC (Man et al. 2015). The conclusion was that the geographic separation from ship environment and screen information presentation techniques constrain the perception of the operator. This can leave very little time available for action due to delayed recognition of the problem and the emergency. In addition, the lack of engine noise, ship motion etc. influences the common ground that the crew team stand upon. For example, when the captain is required for the joint problem-solving, he or she is initially out of the loop and can only develop the situation awareness through extra communication and shared displays. This working arrangement would further prolong the time to resolve urgent issues. While originally, the shared ship sense would let the captain understand the situation more quickly and make a faster decision.

Another issue associated with remote operation is that limited knowledge on the local conditions or language issues would pose communication challenges and introduce uncertainty. It can be challenging to remotely directly maneuver ship from SCC due to noticeable delayed transmission caused by long distance as the signal travels via satellites given the study from space telerobotic operation(Lester et al. 2011, Wahlström et al. 2015).

3.3 Operator modes transition related issues

During the whole voyage, the operator is engaged in different modes, those modes represent different tasks and situations that the operator would be engaged in. The varied modes require different information, skills and knowledge, and cognitive demands. The existence of multiple modes brings up mode confusion if crew members misjudge the current system mode or do not know the exact mode. This gap between the actual system mode and the operator's understanding will cause misinterpretation of ship behavior. For highly autonomous ships, the types of mode transitions include: i) transitions between the operation modes of the same ship, ii) transitions between ships.

3.4 *Technical system & human as work partners*

It is challenging to make automation as a team player (Klien et al. 2004). The collaboration between technical system and humans is limited by 1) information sharing, communication and negotiation, 2) the poor capability of a technical system to evaluate its own situation handling, 3) trust, 4) the authority issue between computer and operator.

It is common that the information displays are not communicative enough, and alarms do not give appropriate feedback. Operators will monitor less effectively when automation is installed, and even more so if the automation has been operating acceptably for a long period, a phenomenon called learned trust (Hoff et al. 2015). The operator may for instance trust decisions the system makes or follow an automatic advice (e.g. route changes that the system recommends and chooses), without checking or verifying against other sources of information. The system is believed to work fine when there are no alerts, but the real situation might be that the autonomous system is reaching its capacity limits and is near to fail. In addition, human operators may misunderstand the signals given by technological aids. People make consistent errors of orientation when using electronic chart displays (Aretz 1991).

3.5 *Rules related issues*

Rules and procedures are commonly used in the operation phase to guide and constrain human behavior. It is not difficult to see that rules and procedures will exist in the operation of autonomous ship, especially in emergency handling. However, many human errors come from rule violation, using wrong rules or over-complying rules. Rule related issues can be discussed in three types of cases. 1) Rules representing the constraints or capabilities, requirements of system operation. Operators need to consider those rules when they are working out a solution. 2) Procedures working in general as a set of rules (algorithms) to control the operator's activity in a certain task or as a "step by step" instruction to guide operator's action to achieve a certain goal (e.g. blackout recover) within the operating constraints. 3) People tend to make their own rules and behave the same way as they successfully did in past repetitive circumstances, neglecting the countersigns of the exceptional or novel circumstances.

3.6 *Teamwork in the operation team*

Cooperation for in-voyage transfer of control between operators has been identified as a critical issue where human error occurs, especially when key information from a previous operator doesn't get passed to later operator.

Teamwork with regards to cooperation and help seeking among roles in the operation team is threatened by 1) situations with unclear problem but high time pressure. 2) over-confidence/low-confidence in problem-solving, 3) unclear responsibility distribution within the team and hidden organizational hierarchy and regulations, 4) miscommunication (Man et al. 2015).

Increased automation reduces crew member's workload and tasks and at the same time change mental demands and teamwork, for example, certain manual tasks will no longer be needed, while new tasks are introduced for the operation of the automated system (Sanquist et al. 1994). Current regulation and rules within crew team might need change to meet the new operation context. For example, captain who take the ultimate responsible when ship is in voyage might not be applicable anymore.

3.7 *Uncertainty related issues*

Uncertainty has been much discussed in the study of decision-making. Uncertainty makes it difficult to project the behavior of environment loads and other vessels and increases the risk. It introduces high levels of concern and frustration to operators in (a) not knowing what would happen and (b) having to delay change until the last minute, when judgements of safety margins are difficult (Hockey et al. 2003).

A number of uncertainties exist. There are uncertainties due to lack of information about the current situation, which can be reduced by communicating and detecting, e.g. uncertainties about the environment, malfunctions, and intentions of other vessels (essential for collision avoidance). Ambiguous, unclear/imprecisely defined operation and organizational rules also adds uncertainty. Furthermore, uncertainty exists due to inaccurate information, leading to misjudgment of problems. Another type of uncertainty comes from the fact that the future is not completely predictable. This includes, for instance, weather, sea traffic or a team member's next action, surprises from the application of techniques like machine learning or artificial intelligence in control algorithms.

3.8 *Goal/sub-goals omission*

There are multi-goals within a ship voyage, including reaching destination according to schedule, watching machinery system, power failures, ship motion, route keeping, avoiding accident like collision. The active goal set changes when situation changes. For instance, the prioritized goal should be shifted from route keeping to collision avoiding when another vessel is approaching. Monitoring machinery system health is needed in the meanwhile.

Goal/sub-goal omission can lead to 1) wrong mental model applied for situation awareness (Endsley 1995); 2) generating and evaluating wrong solution or choice(Klein 1998, Simon 1997). Goal and objectives are usually influenced by organizational culture and values. It also reflects operator's personal value and preferences.

3.9 Mental constraints and characteristics

Advanced automation can reduce the physical workload of operators and change their cognitive tasks much. However, human's attention and cognitive capability is limited. The competition between different tasks is attention competing. Limited attention or inattention would lead to ignorance of key information in the screen display. Cognitive constraints limit the amount of information that humans can process and cause information overload, especially when the operator must handle several ships in a SCC. Other relevant characteristics include: 1) human tend to minimize effort, which may lead to postponement of actions, 2) humans can get tired when monitoring screens for a long time, 3) human tends to get bored if the task is monotonous, and 4) humans can get stressed when exposed high pressure tasks. Stress increases the sharpness of perception to some extents but may also lead to panic and wrong judgment. Chance of action error in precise maneuvers increases when operator faces high pressure. 5) Humans have adaptation and learning capability, creativity, flexibility, ability to see the "big picture", and ability to perform unusual, unplanned tasks. These unique traits make us good problem solvers and accident preventors but also vulnerable to make errors.

3.10 Changes during operation

Ships and SCC are designed to have several decades of lifetime. Software updates, sensor changes etc. cannot be avoided during the whole life-time. Human error due to changes has been discovered by accident investigations and is well acknowledged for safety management in operation. Such errors usually occur a short while after the change has been made.

3.11 Integration of related issues

In addition to what discussed above, experiences, skill and knowledge of crew, detailed automation-interface design including the physical characteristics of control station, reliability and robustness of automated ship functions/sub-functions etc. also challenge crew's performance. All the issues discussed are integrated into the problem recognition, decision making and action, see Figure 4. The colored shapes are the issues discussed above. This descriptive representation shows how those factors influence each element in operator's decision-making process, and the link between them and with ship functions. This figure also shows why the human factor issues are complicated and gives indications about the design and operation variables we can work on to reduce human errors. And it can be further refined and developed into a model for qualitative or quantitative analysis.

4. Possible solutions

To reduce the challenges from human factors, two categories of solutions are proposed in this paper. They are briefly addressed in the following.

4.1 Design-based solutions

To tackle the human factor challenges for the operation of highly autonomous ships, design-based solutions should be prioritized. Many issues discussed in section 3 are relevant to the design of autonomous ship, including LoA design, remote operation related issues, cooperation between operator and the intelligent ship etc. Two categories of approaches can be applied and work together: 1) apply improved design approach, 2) apply certain techniques to improve technical features of the ships in the design phase.

An improved design approach can ease the decision for designers and optimize the design. The improved design approach should be systematic, iterative, life-cycle, involving test and proofing. In the design process, there should be cooperation between operators and producers of highly autonomous ship for knowledge exchange and ultimately eliminate human/ship cooperation problem. To analyze human's involvement, we should start from the overall and life-cycle functionalities of ship agent and SCC, and then analyze human's role in achieving the function and sub-functions.

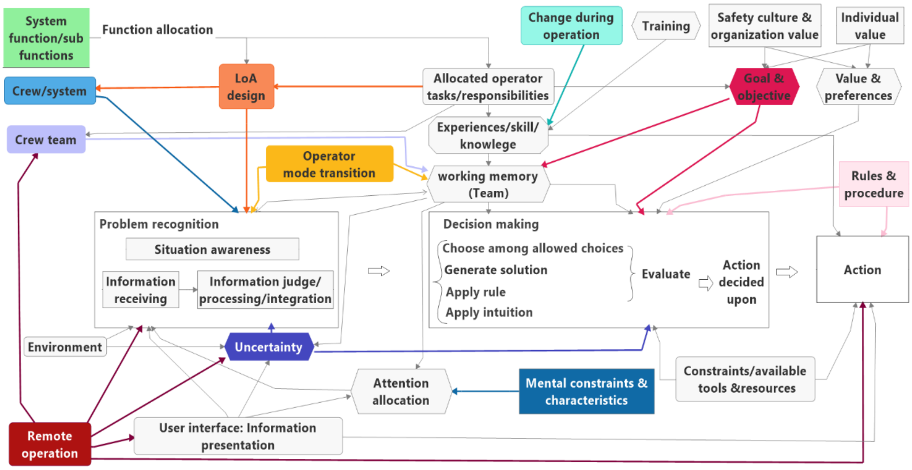

Fig. 4. Integrated representation of human factor related issue

To assess possible human error issues in the design phase, methods include *Task analyses* (Hogenboom et al. 2018), systematic analyses from functions to tasks in the sharp end (Sanquist et al. 1994). The collaboration between system and operator should be evaluated (Karwowski 2005). Empirical data about human error from operation is not rich yet. Therefore, the method for analyzing human factors should be more qualitative than quantitative in the design phase or should be able to handle high uncertainty. The results from the method should be easy to update with different design parameters and used to evaluate and select design solutions.

Optimizing function allocation (FA) is an essential step for the design of autonomous ship(Wright et al. 2000). Dynamic function allocation to the system can be applied (Lagu et al. 2011). FA need to consider both 1) the individual cognitive capabilities of humans and automation reliability, 2) social factors that affect teamwork (Joe et al. 2015). The concept of context-dependent automation (adaptive automation) can be further researched to allow LoAs shift flexibly over time. For the LoA design decision support, Parasuraman et al. (2000) proposed a model that provide a framework and an objective basis for making LoA design choices. Johnson et al. (2014) proposed the interdependence analysis (IA) tool to support LoA decisions. Some design guidelines for the design of Human-autonomy system proposed by Endsley (2017) are also applicable.

Resilience concept and increased the degree of risk tolerance can be implemented in the design to give more flexibility or robustness for human's involvement, for example, give enough separation threshold for collision avoidance due to sensor (in)accuracy, longer response time and maneuverer uncertainty for spatial or temporal separation or both (Theunissen 2014).

There should be a way to indicate the state of emergency and criticality by well-trained operational skill or display indication. Command information is preferable under high emergency even there is a risk of giving wrong command. Status information, which support problem detection and diagnosis, should be used when the circumstances allow the operator uses more time for decision-making or if the consequences of wrong action is severe (Sarter et al. 2001). The information supply from display should support different stages among problem recognition, decision-making and action implementation.

In order to make autonomous ship an effective team player, there should be a two-way flow of information sharing and engagement of team-like behaviors, such as collaboration, coordination, and support for joint planning and re-planning, reprioritization of goals, and reallocation of tasks. To make operator understand what the autonomy is doing, the representation of autonomy behavior should be event-based, future-oriented, pattern-based (Lützhöft et al. 2002). To improve information acquisition and representation for enhancing problem recognition in remote

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operation, techniques such as large shared displays, cameras with live video feed, audio analysis can be implemented. They will be able to increase the reliability of remote operation from SCC (Wahlström et al. 2015). In addition, 4D technique can be a choice to reduce the impact from reduced ship sense due to remote operation.

Uncertainty due to limited knowledge about future safety performance of highly autonomous ships can be reduced by 1) gain experience and learning from other industries; 2) conduct mathematical modeling and simulation (Pritchett 2013); 3) conduct trial tests for various scenarios. This is important to gain system predictability and maintain proper trust. Uncertainty from lack of operational information can be reduced by incorporating information about sea conditions from weather forecast and the intentions of other vessels (for collision avoidance) into decision support design. Information ambiguity should be avoided. For example, engine-off state signal should indicate whether it is a planned engine-off, or someone turned it off, or malfunction. In addition, information uncertainty should be well presented in the interface.

4.2 Operation-based solutions

Training is very much required to develop crew's expertise in operating highly autonomous ship and building up teamwork. It is key to develop remote maneuvering skills and build up system knowledge to develop mental models for situation awareness. The training program need to developed according to the operators task demands especially cognitive task (Sanquist et al. 1994). Periodic training should also be provided to maintain the skills which is rarely required but critical to emergent situations.

To comply with mental constraints, setting moderate mission duration and operation time can be useful to reduce fatigue and inattention. Another suggestion is applying human operator physiological monitors through situation awareness or mental workload monitoring, for example, by monitoring heart rate. Those monitors could give alerts when operator loses attention in monitoring or faces high stress.

Interaction and automation trust check can be conducted in regular bases to prevent procedure violation or over/under trust issue after certain length of operation time.

As for uncertainty handling in operation phase, constraining operation environment and conditions can limit the threats from sea condition and avoid heavy traffic. Using Rules-of-the-road constraints could make the course changes for target vessels more predictable (Hockey et al. 2003).

5. Concluding remarks

Overall, the autonomous ship development is towards an increased degree of autonomy however limited by the availability and reliability of technology. Human will still play a critical role in the operation. Even though human errors from most boring and routine-oriented tasks are reduced. The critical and complicated decisions human operators must make and quick response form challenges. Managing decision-making in complex situations and risk information for making good decisions is the key to maintain high human reliability. The proposed integrated representation of human factor related issues and problem recognition - decision-making - action process can be further refined and developed into a model for qualitative or quantitative analysis.

High uncertainties exist due to many possible paths in design and future operation arrangement. Detailed regulation, guidance and good practice for design and operation are not established yet. This allows more opportunities to establish a safe system. The many described solutions can be further developed to easy the human factor issues to achieve the long-term safe operation of highly autonomous ships.

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Article 3

Characterization of risk-related decision problems

Tiantian Zhu, Stein Haugen, Yiliu Liu and Xue Yang.

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This paper is submitted for publication and is therefore not included.

Article 4

Case study of major accident to demonstrate the possibility of prediction of conditions for accidents

Tiantian Zhu, Stein Haugen, Yiliu Liu and Kim Hyungju.

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Article 5

A value of prediction model to estimate optimal response time to threats for accident prevention

Tiantian Zhu, Stein Haugen, Yiliu Liu and Xue Yang.

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		deck slamming. (Dr.Ing. Thesis)
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IMT-2008-38	Harlem, Alf	An Age-Based Replacement Model for Repairable Systems with Attention to High-Speed Marine Diesel Engines. (PhD-Thesis, IMT)
IMT-2008-39	Alsos, Hagbart S.	Ship Grounding. Analysis of Ductile Fracture, Bottom Damage and Hull Girder Response. (PhD-thesis, IMT)
IMT-2008-40	Graczyk, Mateusz	Experimental Investigation of Sloshing Loading and Load Effects in Membrane LNG Tanks Subjected to Random Excitation. (PhD-thesis, CeSOS)
IMT-2008-41	Taghipour, Reza	Efficient Prediction of Dynamic Response for Flexible amd Multi-body Marine Structures. (PhD-thesis, CeSOS)
IMT-2008-42	Ruth, Eivind	Propulsion control and thrust allocation on marine vessels. (PhD thesis, CeSOS)
IMT-2008-43	Nystad, Bent Helge	Technical Condition Indexes and Remaining Useful Life of Aggregated Systems. PhD thesis, IMT
IMT-2008-44	Soni, Prashant Kumar	Hydrodynamic Coefficients for Vortex Induced Vibrations of Flexible Beams, PhD thesis, CeSOS
IMT-2009-45	Amlashi, Hadi K.K.	Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD Thesis, IMT
IMT-2009-46	Pedersen, Tom Arne	Bond Graph Modelling of Marine Power Systems. PhD Thesis, IMT
IMT-2009-47	Kristiansen, Trygve	Two-Dimensional Numerical and Experimental Studies of Piston-Mode Resonance. PhD-Thesis, CeSOS
IMT-2009-48	Ong, Muk Chen	Applications of a Standard High Reynolds Number Model and a Stochastic Scour Prediction Model for Marine Structures. PhD-thesis, IMT

IMT-2009-49	Hong, Lin	Simplified Analysis and Design of Ships subjected to Collision and Grounding. PhD-thesis, IMT
IMT-2009-50	Koushan, Kamran	Vortex Induced Vibrations of Free Span Pipelines, PhD thesis, IMT
IMT-2009-51	Korsvik, Jarl Eirik	Heuristic Methods for Ship Routing and Scheduling. PhD-thesis, IMT
IMT-2009-52	Lee, Jihoon	Experimental Investigation and Numerical in Analyzing the Ocean Current Displacement of Longlines. Ph.d.-Thesis, IMT.
IMT-2009-53	Vestbøstad, Tone Gran	A Numerical Study of Wave-in-Deck Impact usin a Two-Dimensional Constrained Interpolation Profile Method, Ph.d.thesis, CeSOS.
IMT-2009-54	Bruun, Kristine	Bond Graph Modelling of Fuel Cells for Marine Power Plants. Ph.d.-thesis, IMT
IMT 2009-55	Holstad, Anders	Numerical Investigation of Turbulence in a Sekwed Three-Dimensional Channel Flow, Ph.d.-thesis, IMT.
IMT 2009-56	Ayala-Uraga, Efren	Reliability-Based Assessment of Deteriorating Ship-shaped Offshore Structures, Ph.d.-thesis, IMT
IMT 2009-57	Kong, Xiangjun	A Numerical Study of a Damaged Ship in Beam Sea Waves. Ph.d.-thesis, IMT/CeSOS.
IMT 2010-58	Kristiansen, David	Wave Induced Effects on Floaters of Aquaculture Plants, Ph.d.-thesis, CeSOS.
IMT 2010-59	Ludvigsen, Martin	An ROV-Toolbox for Optical and Acoustic Scientific Seabed Investigation. Ph.d.-thesis IMT.
IMT 2010-60	Hals, Jørgen	Modelling and Phase Control of Wave-Energy Converters. Ph.d.thesis, CeSOS.
IMT 2010- 61	Shu, Zhi	Uncertainty Assessment of Wave Loads and Ultimate Strength of Tankers and Bulk Carriers in a Reliability Framework. Ph.d. Thesis, IMT/ CeSOS
IMT 2010-62	Shao, Yanlin	Numerical Potential-Flow Studies on Weakly-Nonlinear Wave-Body Interactions with/without Small Forward Speed, Ph.d.thesis,CeSOS.
IMT 2010-63	Califano, Andrea	Dynamic Loads on Marine Propellers due to Intermittent Ventilation. Ph.d.thesis, IMT.
IMT 2010-64	El Khoury, George	Numerical Simulations of Massively Separated Turbulent Flows, Ph.d.-thesis, IMT
IMT 2010-65	Seim, Knut Sponheim	Mixing Process in Dense Overflows with Emphasis on the Faroe Bank Channel Overflow. Ph.d.thesis, IMT

IMT 2010-66	Jia, Huirong	Structural Analysis of Intect and Damaged Ships in a Collission Risk Analysis Perspective. Ph.d.thesis CeSoS.
IMT 2010-67	Jiao, Linlin	Wave-Induced Effects on a Pontoon-type Very Large Floating Structures (VLFS). Ph.D.-thesis, CeSOS.
IMT 2010-68	Abrahamsen, Bjørn Christian	Sloshing Induced Tank Roof with Entrapped Air Pocket. Ph.d.thesis, CeSOS.
IMT 2011-69	Karimirad, Madjid	Stochastic Dynamic Response Analysis of Spar-Type Wind Turbines with Catenary or Taut Mooring Systems. Ph.d.-thesis, CeSOS.
IMT -2011-70	Erlend Meland	Condition Monitoring of Safety Critical Valves. Ph.d.-thesis, IMT.
IMT – 2011-71	Yang, Limin	Stochastic Dynamic System Analysis of Wave Energy Converter with Hydraulic Power Take-Off, with Particular Reference to Wear Damage Analysis, Ph.d. Thesis, CeSOS.
IMT – 2011-72	Visscher, Jan	Application of Particla Image Velocimetry on Turbulent Marine Flows, Ph.d.Thesis, IMT.
IMT – 2011-73	Su, Biao	Numerical Predictions of Global and Local Ice Loads on Ships. Ph.d.Thesis, CeSOS.
IMT – 2011-74	Liu, Zhenhui	Analytical and Numerical Analysis of Iceberg Collision with Ship Structures. Ph.d.Thesis, IMT.
IMT – 2011-75	Aarsæther, Karl Gunnar	Modeling and Analysis of Ship Traffic by Observation and Numerical Simulation. Ph.d.Thesis, IMT.
Imt – 2011-76	Wu, Jie	Hydrodynamic Force Identification from Stochastic Vortex Induced Vibration Experiments with Slender Beams. Ph.d.Thesis, IMT.
Imt – 2011-77	Amini, Hamid	Azimuth Propulsors in Off-design Conditions. Ph.d.Thesis, IMT.
IMT – 2011-78	Nguyen, Tan-Hoi	Toward a System of Real-Time Prediction and Monitoring of Bottom Damage Conditions During Ship Grounding. Ph.d.thesis, IMT.
IMT- 2011-79	Tavakoli, Mohammad T.	Assessment of Oil Spill in Ship Collision and Grounding, Ph.d.thesis, IMT.
IMT- 2011-80	Guo, Bingjie	Numerical and Experimental Investigation of Added Resistance in Waves. Ph.d.Thesis, IMT.

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IMT-2012-82	Kota, Ravikiran S.	Wave Loads on Decks of Offshore Structures in Random Seas, CeSOS.
IMT-2012-83	Sten, Ronny	Dynamic Simulation of Deep Water Drilling Risers with Heave Compensating System, IMT.
IMT-2012-84	Berle, Øyvind	Risk and resilience in global maritime supply chains, IMT.
IMT-2012-85	Fang, Shaoji	Fault Tolerant Position Mooring Control Based on Structural Reliability, CeSOS.
IMT-2012-86	You, Jikun	Numerical studies on wave forces and moored ship motions in intermediate and shallow water, CeSOS.
IMT-2012-87	Xiang ,Xu	Maneuvering of two interacting ships in waves, CeSOS
IMT-2012-88	Dong, Wenbin	Time-domain fatigue response and reliability analysis of offshore wind turbines with emphasis on welded tubular joints and gear components, CeSOS
IMT-2012-89	Zhu, Suji	Investigation of Wave-Induced Nonlinear Load Effects in Open Ships considering Hull Girder Vibrations in Bending and Torsion, CeSOS
IMT-2012-90	Zhou, Li	Numerical and Experimental Investigation of Station-keeping in Level Ice, CeSOS
IMT-2012-91	Ushakov, Sergey	Particulate matter emission characteristics from diesel enignes operating on conventional and alternative marine fuels, IMT
IMT-2013-1	Yin, Decao	Experimental and Numerical Analysis of Combined In-line and Cross-flow Vortex Induced Vibrations, CeSOS
IMT-2013-2	Kurniawan, Adi	Modelling and geometry optimisation of wave energy converters, CeSOS
IMT- 2013-3	Al Ryati, Nabil	Technical condition indexes doe auxiliary marine diesel engines, IMT
IMT-2013-4	Firoozkoohi, Reza	Experimental, numerical and analytical investigation of the effect of screens on sloshing, CeSOS
IMT-2013-5	Ommani, Babak	Potential-Flow Predictions of a Semi-Displacement Vessel Including Applications to Calm Water Broaching, CeSOS
IMT- 2013-6	Xing, Yihan	Modelling and analysis of the gearbox in a floating spar-type wind turbine, CeSOS

IMT-7-2013	Balland, Océane	Optimization models for reducing air emissions from ships, IMT
IMT-8-2013	Yang, Dan	Transitional wake flow behind an inclined flat plate-----Computation and analysis, IMT
IMT-9-2013	Abdillah, Suyuthi	Prediction of Extreme Loads and Fatigue Damage for a Ship Hull due to Ice Action, IMT
IMT-10-2013	Ramìrez, Pedro Agustìn Pèrez	Ageing management and life extension of technical systems- Concepts and methods applied to oil and gas facilities, IMT
IMT-11-2013	Chuang, Zhenju	Experimental and Numerical Investigation of Speed Loss due to Seakeeping and Maneuvering. IMT
IMT-12-2013	Etemaddar, Mahmoud	Load and Response Analysis of Wind Turbines under Atmospheric Icing and Controller System Faults with Emphasis on Spar Type Floating Wind Turbines, IMT
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IMT-14-2013	Haris, Sabril	Damage interaction analysis of ship collisions, IMT
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IMT-16-2013	Gansel, Lars	Flow past porous cylinders and effects of biofouling and fish behavior on the flow in and around Atlantic salmon net cages, IMT
IMT-17-2013	Gaspar, Henrique	Handling Aspects of Complexity in Conceptual Ship Design, IMT
IMT-18-2013	Thys, Maxime	Theoretical and Experimental Investigation of a Free Running Fishing Vessel at Small Frequency of Encounter, CeSOS
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IMT-1-2014	Song, An	Theoretical and experimental studies of wave diffraction and radiation loads on a horizontally submerged perforated plate, CeSOS
IMT-2-2014	Rogne, Øyvind Ygre	Numerical and Experimental Investigation of a Hinged 5-body Wave Energy Converter, CeSOS
IMT-3-2014	Dai, Lijuan	Safe and efficient operation and maintenance of offshore wind farms ,IMT
IMT-4-2014	Bachynski, Erin Elizabeth	Design and Dynamic Analysis of Tension Leg Platform Wind Turbines, CeSOS
IMT-5-2014	Wang, Jingbo	Water Entry of Freefall Wedged – Wedge motions

		and Cavity Dynamics, CeSOS
IMT-6-2014	Kim, Ekaterina	Experimental and numerical studies related to the coupled behavior of ice mass and steel structures during accidental collisions, IMT
IMT-7-2014	Tan, Xiang	Numerical investigation of ship's continuous- mode icebreaking in leverl ice, CeSOS
IMT-8-2014	Muliawan, Made Jaya	Design and Analysis of Combined Floating Wave and Wind Power Facilities, with Emphasis on Extreme Load Effects of the Mooring System, CeSOS
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IMT-10-2014	Dukan, Fredrik	ROV Motion Control Systems, IMT
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IMT-13-2014	Akhtar, Juned	The Effects of Human Fatigue on Risk at Sea, IMT
IMT-14-2014	Syahroni, Nur	Fatigue Assessment of Welded Joints Taking into Account Effects of Residual Stress, IMT
IMT-1-2015	Bøckmann, Eirik	Wave Propulsion of ships, IMT
IMT-2-2015	Wang, Kai	Modelling and dynamic analysis of a semi-submersible floating vertical axis wind turbine, CeSOS
IMT-3-2015	Fredriksen, Arnt Gunvald	A numerical and experimental study of a two-dimensional body with moonpool in waves and current, CeSOS
IMT-4-2015	Jose Patricio Gallardo Canabes	Numerical studies of viscous flow around bluff bodies, IMT
IMT-5-2015	Vegard Longva	Formulation and application of finite element techniques for slender marine structures subjected to contact interactions, IMT
IMT-6-2015	Jacobus De Vaal	Aerodynamic modelling of floating wind turbines, CeSOS
IMT-7-2015	Fachri Nasution	Fatigue Performance of Copper Power Conductors, IMT

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IMT-9-2015	Daniel de Almeida Fernandes	An output feedback motion control system for ROVs, AMOS
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IMT-1-2016	Vincentius Rumawas	Human Factors in Ship Design and Operation: An Experiential Learning, IMT
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IMT-3-2016	Mia Abrahamsen Prsic	Numerical Simulations of the Flow around single and Tandem Circular Cylinders Close to a Plane Wall, IMT
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IMT-5-2016	Pierre Yves-Henry	Parametrisation of aquatic vegetation in hydraulic and coastal research,IMT
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IMT-8-2016	Xiaopeng Wu	Numerical Analysis of Anchor Handling and Fish Trawling Operations in a Safety Perspective, CeSOS
IMT-9-2016	Zhengshun Cheng	Integrated Dynamic Analysis of Floating Vertical Axis Wind Turbines, CeSOS
IMT-10-2016	Ling Wan	Experimental and Numerical Study of a Combined Offshore Wind and Wave Energy Converter Concept
IMT-11-2016	Wei Chai	Stochastic dynamic analysis and reliability evaluation of the roll motion for ships in random seas, CeSOS
IMT-12-2016	Øyvind Selnes Patricksson	Decision support for conceptual ship design with focus on a changing life cycle and future uncertainty, IMT
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IMT-1-2017	Mohammad Saud Afzal	Three-dimensional streaming in a sea bed boundary layer
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IMT-6-2017	Fatemeh Hoseini Dadmarzi	Direct Numerical Simualtion of turbulent wakes behind different plate configurations
IMT-7-2017	Michel R. Miyazaki	Modeling and control of hybrid marine power plants
IMT-8-2017	Giri Rajasekhar Gunnu	Safety and effiency enhancement of anchor handling operations with particular emphasis on the stability of anchor handling vessels
IMT-9-2017	Kevin Koosup Yum	Transient Performance and Emissions of a Turbocharged Diesel Engine for Marine Power Plants
IMT-10-2017	Zhaolong Yu	Hydrodynamic and structural aspects of ship collisions
IMT-11-2017	Martin Hassel	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations
IMT-12-2017	Astrid H. Brodtkorb	Hybrid Control of Marine Vessels – Dynamic Positioning in Varying Conditions
IMT-13-2017	Kjersti Bruserud	Simultaneous stochastic model of waves and current for prediction of structural design loads
IMT-14-2017	Finn-Idar Grøtta Giske	Long-Term Extreme Response Analysis of Marine Structures Using Inverse Reliability Methods
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IMT-1-2018	Yingguang Chu	Virtual Prototyping for Marine Crane Design and Operations
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IMT-6-2018	Bård Stovner	Aided Intertial Navigation of Underwater Vehicles

IMT-7-2018	Erlend Liavåg Grotle	Thermodynamic Response Enhanced by Sloshing in Marine LNG Fuel Tanks
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IMT-9-2018	Jan Vidar Ulveseter	Advances in Semi-Empirical Time Domain Modelling of Vortex-Induced Vibrations
IMT-10-2018	Chenyu Luan	Design and analysis for a steel braceless semi-submersible hull for supporting a 5-MW horizontal axis wind turbine
IMT-11-2018	Carl Fredrik Rehn	Ship Design under Uncertainty
IMT-12-2018	Øyvind Ødegård	Towards Autonomous Operations and Systems in Marine Archaeology
IMT-13- 2018	Stein Melvær Nornes	Guidance and Control of Marine Robotics for Ocean Mapping and Monitoring
IMT-14-2018	Petter Norgren	Autonomous Underwater Vehicles in Arctic Marine Operations: Arctic marine research and ice monitoring
IMT-15-2018	Minjoo Choi	Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context
MT-16-2018	Ole Alexander Eidsvik	Dynamics of Remotely Operated Underwater Vehicle Systems
IMT-17-2018	Mahdi Ghane	Fault Diagnosis of Floating Wind Turbine Drivetrain- Methodologies and Applications
IMT-18-2018	Christoph Alexander Thieme	Risk Analysis and Modelling of Autonomous Marine Systems
IMT-19-2018	Yugao Shen	Operational limits for floating-collar fish farms in waves and current, without and with well-boat presence
IMT-20-2018	Tianjiao Dai	Investigations of Shear Interaction and Stresses in Flexible Pipes and Umbilicals
IMT-21-2018	Sigurd Solheim Pettersen	Resilience by Latent Capabilities in Marine Systems
IMT-22-2018	Thomas Sauder	Fidelity of Cyber-physical Empirical Methods. Application to the Active Truncation of Slender Marine Structures
IMT-23-2018	Jan-Tore Horn	Statistical and Modelling Uncertainties in the Design of Offshore Wind Turbines

IMT-24-2018	Anna Swider	Data Mining Methods for the Analysis of Power Systems of Vessels
IMT-1-2019	Zhao He	Hydrodynamic study of a moored fish farming cage with fish influence
IMT-2-2019	Isar Ghamari	Numerical and Experimental Study on the Ship Parametric Roll Resonance and the Effect of Anti-Roll Tank
IMT-3-2019	Håkon Strandenes	Turbulent Flow Simulations at Higher Reynolds Numbers
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IMT-5-2019	Ping Fu	Reliability Analysis of Wake-Induced Riser Collision
IMT-6-2019	Vladimir Krivopolianskii	Experimental Investigation of Injection and Combustion Processes in Marine Gas Engines using Constant Volume Rig
IMT-7-2019	Anna Maria Kozlowska	Hydrodynamic Loads on Marine Propellers Subject to Ventilation and out of Water Condition.
IMT-8-2019	Hans-Martin Heyn	Motion Sensing on Vessels Operating in Sea Ice: A Local Ice Monitoring System for Transit and Stationkeeping Operations under the Influence of Sea Ice
IMT-9-2019	Stefan Vilsen	Method for Real-Time Hybrid Model Testing of Ocean Structures – Case on Slender Marine Systems
IMT-10-2019	Finn-Christian W. Hanssen	Non-Linear Wave-Body Interaction in Severe Waves
IMT-11-2019	Trygve Olav Fossum	Adaptive Sampling for Marine Robotics
IMT-12-2019	Jørgen Bremnes Nielsen	Modeling and Simulation for Design Evaluation
IMT-13-2019	Yuna Zhao	Numerical modelling and dyncamic analysis of offshore wind turbine blade installation
IMT-14-2019	Daniela Myland	Experimental and Theoretical Investigations on the Ship Resistance in Level Ice
IMT-15-2019	Zhengru Ren	Advanced control algorithms to support automated offshore wind turbine installation
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IMT-17-2019	Endre Sandvik	Sea passage scenario simulation for ship system performance evaluation
IMT-18-2019	Loup Suja-Thauvin	Response of Monopile Wind Turbines to Higher Order Wave Loads
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IMT-20-2019	Aleksandar-Sasa Milakovic	On equivalent ice thickness and machine learning in ship ice transit simulations
IMT-1-2020	Amrit Shankar Verma	Modelling, Analysis and Response-based Operability Assessment of Offshore Wind Turbine Blade Installation with Emphasis on Impact Damages
IMT-2-2020	Bent Oddvar Arnesen Haugaløkken	Autonomous Technology for Inspection, Maintenance and Repair Operations in the Norwegian Aquaculture
IMT-3-2020	Seongpil Cho	Model-based fault detection and diagnosis of a blade pitch system in floating wind turbines
IMT-4-2020	Jose Jorge Garcia Agis	Effectiveness in Decision-Making in Ship Design under Uncertainty
IMT-5-2020	Thomas H. Viuff	Uncertainty Assessment of Wave-and Current-induced Global Response of Floating Bridges
IMT-6-2020	Fredrik Mentzoni	Hydrodynamic Loads on Complex Structures in the Wave Zone
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IMT-8-2020	Stian Skaalvik Sandøy	Acoustic-based Probabilistic Localization and Mapping using Unmanned Underwater Vehicles for Aquaculture Operations
IMT-9-2020	Kun Xu	Design and Analysis of Mooring System for Semi-submersible Floating Wind Turbine in Shallow Water
IMT-10-2020	Jianxun Zhu	Cavity Flows and Wake Behind an Elliptic Cylinder Translating Above the Wall
IMT-11-2020	Sandra Hogenboom	Decision-making within Dynamic Positioning Operations in the Offshore Industry – A Human Factors based Approach
IMT-12-2020	Woongshik Nam	Structural Resistance of Ship and Offshore Structures Exposed to the Risk of Brittle Failure
IMT-13-2020	Svenn Are Tutturen Værnø	Transient Performance in Dynamic Positioning of Ships: Investigation of Residual Load Models and Control Methods for Effective Compensation

IMT-14-2020	Mohd Atif Siddiqui	Experimental and Numerical Hydrodynamic Analysis of a Damaged Ship in Waves
IMT-15-2020	John Marius Hegseth	Efficient Modelling and Design Optimization of Large Floating Wind Turbines
IMT-16-2020	Asle Natskår	Reliability-based Assessment of Marine Operations with Emphasis on Sea Transport on Barges
IMT-17-2020	Shi Deng	Experimental and Numerical Study of Hydrodynamic Responses of a Twin-Tube Submerged Floating Tunnel Considering Vortex-Induced Vibration
IMT-18-2020	Jone Torsvik	Dynamic Analysis in Design and Operation of Large Floating Offshore Wind Turbine Drivetrains
IMT-1-2021	Ali Ebrahimi	Handling Complexity to Improve Ship Design Competitiveness
IMT-2-2021	Davide Proserpio	Isogeometric Phase-Field Methods for Modeling Fracture in Shell Structures
IMT-3-2021	Cai Tian	Numerical Studies of Viscous Flow Around Step Cylinders
IMT-4-2021	Farid Khazaeli Moghadam	Vibration-based Condition Monitoring of Large Offshore Wind Turbines in a Digital Twin Perspective
IMT-5-2021	Shuaishuai Wang	Design and Dynamic Analysis of a 10-MW Medium-Speed Drivetrain in Offshore Wind Turbines
IMT-6-2021	Sadi Tavakoli	Ship Propulsion Dynamics and Emissions
IMT-7-2021	Haoran Li	Nonlinear wave loads, and resulting global response statistics of a semi-submersible wind turbine platform with heave plates
IMT-8-2021	Einar Skiftestad Ueland	Load Control for Real-Time Hybrid Model Testing using Cable-Driven Parallel Robots
IMT-9-2021	Mengning Wu	Uncertainty of machine learning-based methods for wave forecast and its effect on installation of offshore wind turbines
IMT-10-2021	Xu Han	Onboard Tuning and Uncertainty Estimation of Vessel Seakeeping Model Parameters
IMT-01-2022	Ingunn Marie Holmen	Safety in Exposed Aquacultrue Operations
IMT-02-2022	Prateek Gupta	Ship Performance Monitoring using In-service Measurements and Big Data Analysis Methods

IMT-03-2022	Sangwoo Kim	Non-linear time domain analysis of deepwater riser vortex-induced vibrations
IMT-04-2022	Jarle Vinje Kramer	Hydrodynamic Aspects of Sail-Assisted Merchant Vessels
IMT-05-2022	Øyvind Rabliås	Numerical and Expermental Studies of Maneuvering in Regular and Irregular Waves
IMT-06-2022	Pramod Ghimire	Simulation-Based Ship Hybrid Power System Conspet Studies and Performance Analyses
IMT-07-2022	Carlos Eduardo Silva de Souza	Structural modelling, coupled dynamics, and design of large floating wind turbines
IMT-08-2022	Lorenzo Balestra	Design of hybrid fuel cell & battery systems for maritime vessels
IMT-09-2022	Sharmin Sultana	Process safety and risk management using system perspectives – A contribution to the chemical process and petroleum industry
IMT-10-2022	Øystein Sture	Autonomous Exploration for Marine Minerals
IMT-11-2022	Tiantian Zhu	Information and Decision-making for Major Accident Prevention – A concept of information-based strategies for accident prevention