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Ruochen Yang

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Thesis for the degree of
Philosophiae Doctor
Faculty of Engineering
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Preface

This thesis is submitted in partial fulfillment of the requirements for the degree of Philosophiae Doctor (PhD) at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The PhD work was carried out at the Department of Marine Technology at NTNU in the period between September 2019 to September 2022. The research presented in this thesis was carried under the principal supervision of Professor Ingrid Bouwer Utne, and the co-supervision of Professor Martin Ludvigsen and Professor Ingrid Schjølberg.

The PhD work was funded by the Research Council of Norway through the Nansen Legacy project with project number RCN#276730.

This thesis is divided into two parts: the first part provides a synthesis of the objectives, background material, relevant literatures, and contributions of the PhD project. The second part is a collection of five research articles which constitute the main results of the work conducted.

The target audience of this thesis is researchers and practitioners that working with risk assessment, safety engineering, and maintenance planning of autonomous marine systems. The developed methods/models and the conclusions from the presented research may influence the future design and operation of the autonomous marine systems or other types of autonomous systems.

Ruochen Yang

Trondheim, October 2022

Summary

Autonomous marine systems (AMS), such as autonomous underwater vehicles (AUVs), and unmanned surface vehicles (USVs) have evolved over the past decades. Maritime autonomous surface ships (MASS) are gradually being developed and commissioned. AMS are applied in different types of industries and research. Examples include the application of USVs or AUVs for ocean monitoring, and the development of MASS for future cargo and personnel transportation.

In these operations, AMS can help reduce the risk of personnel exposure to harsh environments, reduce the operational costs, and improve the efficiency and performance of the human operators. However, compared to conventional marine systems, new types of failure might be introduced to AMS operations due to unforeseen interdependencies in the system design, dynamic operating environments, maintenance challenges, insufficient situation awareness and decision-making from human operators, etc. Also, AMS functions are constantly being improved, and the operations of AMS are becoming more complex and advanced. The safety issues of these systems have become even more critical. Techniques for analyzing and controlling the safety of AMS operations are therefore required.

The overall aim of this PhD project is to develop methods and models for analyzing and controlling safety in operations of AMS. It is refined into the following three research objectives that are addressed in five research articles:

- Identify and analyze hazards and hazardous events in the operation of autonomous marine systems and evaluate the applicability of relevant methods as a basis for online risk modeling of autonomous marine systems.
- Analyze the dynamic changes in the operating environment and system status, and model their impacts on the safe operation.
- Propose a general method for developing online risk models for autonomous marine systems and operations, supporting risk-based control.

The work presented here reviews the existing methods and models and identifies the main research challenges and gaps with respect to the above research objectives. The research presented in the thesis addressed some of these issues. The main contributions of this thesis are summarized as follows:

- Investigation of the potential hazards/ hazardous events during the operation with multiple AMS and how these hazards/ hazardous events may affect the safe and reliable

operations of AMS. The results highlight the importance of considering unsafe interactions in hazard identification or risk assessment in AMS operations.

- Comprehensive hazard identification works with a number of potential hazards/ hazardous events that may affect the safe operation of an under-ice AUV operation through various methods. The results contribute research and practical implications for improved engineering design and operational procedures to enhance the safety and robustness of future AMS operations in the Arctic.
- Identification of a list of evaluation criteria for online risk models for AMS and comprehensive evaluation of the applicability of several existing methods for online risk modeling of AMS. The evaluation results contribute to an appropriate first step towards a general framework for online risk modeling for AMS.
- Proposal for a dynamic risk analysis method to determine the dynamic changes in the operating environment and assess the environmental impact on the safe operation of AMS.
- Proposal for a novel dynamic maintenance planning method for AMS that addresses challenges in maintenance planning, including the high consequence of system shutdown, limited and irregular maintenance opportunities, and various dependencies among components.
- Proposal for a general framework for the online risk modeling of AMS to enhance the intelligence of the AMS, its situation awareness, and decision-making. The proposed framework addresses several challenges in developing online risk modeling, e.g., evidence uncertainty.
- Proposal for a two-level strategy to develop a supervisory risk control (SRC) system for AMS operations based on the developed online risk model. The SRC system can improve the intelligence of AMS by enabling its risk-based control.

In conclusion, the research and findings presented in the thesis provide researchers and practitioners in the field with a comprehensive overview of safety issues in AMS operations, and novel methods and models for analyzing and handling these. The proposed methods and models are expected to improve the safety of future AMS operations.

Acknowledgement

First and foremost, I would express the deepest gratitude to my supervisor, Professor Ingrid Bouwer Utne, for her constant support and encouragement during the period of my PhD work. She encouraged me to think independently and critically during the research process, while providing detailed, practical, and timely feedback when needed. The experience of working with her has inspired me during my journey of learning to be a researcher.

I would like to thank Professor Jørn Vatn from Department of Mechanical and Industrial Engineering at NTNU. He provided insightful and constructive comments and suggestions on the journal article related to maintenance planning. I am also indebted to Jens Einar Bremnes for his help when developing the simulator of autonomous underwater vehicle and great discussion on research ideas during the collaboration. Professor Yiliu Liu and Professor Nicola Paltrinieri have contributed to my work with practical and valuable suggestions. I appreciate their input to my work. I also want to thank Dr. Lorenzo Balestra for the excellent collaboration on the research, where I could contribute as a co-author.

Some of the research presented in this thesis was conducted in collaboration with the Advanced Underwater Robotics Laboratory at NTNU. In particular, I would like to thank Professor Martin Ludvigsen, Tore Mo-Bjørkelund, and Dr. Petter Norgren for providing practical information and experience on the operations of autonomous marine systems and possible safety challenges. I had opportunities to participate several research cruises with RV Kronprins Haakon and RV Gunnerus. These field trips provided me with first-hand knowledge of operations of autonomous marine systems. Thanks go to the crew of these two research vessels for their support and help.

I am grateful to all my colleagues and friends in the Department of Marine Technology at NTNU. Thank you all for the lunch and coffee break. I enjoyed all the interesting discussions and activities we had. It has been my fortune to study and work with these dynamic young researchers. Especially, thanks go to my office mate, Thomas Johansen, who has been a great fellow traveler in my journey pursuing PhD.

I would like to thank my parents, Pengfei Yang and Saichou Zhang, who have encouraged and energized me from thousands of miles away. Lastly, many thanks go to Yaqi Yang, my girlfriend, for her continued love, understanding, and support.

Publications

The following research articles are included in Part II of this thesis. They provide detailed information on the results and contributions that are presented in Part I.

Article 1 – Conference article

Yang, R., Bremnes, J. E. and Utne, I. B. (2022). A system-theoretic approach to hazard identification of operation with multiple autonomous marine systems (AMS). *Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)*, Ireland.

Article 2 – Journal article

Yang, R. and Utne, I. B. (2022). Towards an online risk model for autonomous marine systems (AMS). *Ocean Engineering* 251: 111100.

Article 3 – Conference article

Yang, R., Utne, I. B., Liu, Y. and Paltrinieri, N. (2020). Dynamic risk analysis of operation of the autonomous underwater vehicle (AUV). *Proceedings of the 30th European Safety and Reliability Conference andthe 15th Probabilistic Safety Assessment and Management Conference*, Italy.

Article 4 – Journal article

Yang, R., Vatn, J. and Utne, I. B. (2022). Dynamic maintenance planning for autonomous marine systems (AMS) and operations. *Submitted to Ocean Engineering.*

Status – Under review.

Article 5 – Journal article

Yang, R., Bremnes, J. E. and Utne, I. B. (2022). Online risk modeling of autonomous marine system: a case study of autonomous under-ice operation. *Submitted to Ocean Engineering.*

Status – Under review.

Declaration of authorship

Ingrid Bouwer Utne, Jens Einar Bremnes, Jørn Vatn, Yiliu Liu, and Nicola Paltrinieri are the coauthors of one or several articles included in this thesis. The contribution of the candidate and coauthors are presented according to the following tasks:

1. Research idea and concept
2. Data collection
3. Data analysis
4. Manuscript drafting
5. Manuscript critical review

The contributions of each author were as follows:

Author	Article 1	Article 2	Article 3	Article 4	Article 5
Ruochen Yang	1-5	1-5	1-5	1-5	1-5
Ingrid Bouwer Utne	5	1, 2, 5	1, 5	5	1, 5
Jens Einar Bremnes	3, 5	-	-	-	1, 4, 5
Jørn Vatn	-	-	-	1, 5	-
Yiliu Liu	-	-	1, 5	-	-
Nicola Paltrinieri	-	-	1, 5	-	-

Publications not included in this thesis

During the PhD period, one more publication was produced, which is not included in the thesis.

Article 6

Balestra, L., Yang, R., Schjølberg, I., Utne, I.B. and Ulleberg, Ø. (2021). Towards safety barrier analysis of hydrogen powered maritime vessels. *In International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 85161, p. V006T06A016). American Society of Mechanical Engineers.

Contents

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Abbreviations

AMS	Autonomous marine systems
ALARP	As low as reasonably practicable
AROV	Autonomous remotely operated vehicle
AUR Lab	Applied Underwater Robotics Laboratory
AUV	Autonomous underwater vehicle
BBNs	Bayesian belief networks
BT	Bow-tie
CMBRA	Condition monitoring-based risk assessment
DBN	Dynamic Bayesian network
DDN	Dynamic decision network
DRA	Dynamic risk assessment
ETA	Event tree analysis
FMEA	Failure mode and effects analysis
FPSO	Floating production storage offloading
FTA	Fault tree analysis
HAZOP	Hazard and operability analysis
HMI	Human-machine interface
KooN	k-out-of-n
LoA	Level of autonomy
MASS	Maritime autonomous surface ships
MUNIN	Maritime unmanned navigation through intelligence in networks
NTNU	Norwegian University of Science and Technology
OOBN	Object-oriented Bayesian network
PHA	Preliminary hazard analysis
PhD	Philosophiae doctor

PHM	Prognostics and health management
PRA	Probabilistic risk assessment
RIF	Risk influencing factor
RO	Research objective
ROV	Remotely operated vehicle
SCC	Shore control center
SRC	Supervisory risk control
STPA	System theoretic process analysis
UAV	Unmanned aerial vehicle
UCA	Unsafe control actions
USBL	Ultra-short baseline
USV	Unmanned surface vehicle
UUV	Unmanned underwater vehicle

Part I - Main Report

1 Introduction

1.1 Background and motivation

The research presented in this thesis has been part of the research project the Nansen Legacy[1]. This research project focuses on the marine environment and natural resources of the Barents Sea and adjacent Arctic Basin, and it provides integrated scientific knowledge for their sustainable management.

The marine environment is vast, harsh, and challenging. Ocean monitoring and data collection, maritime transportation, sea based aquaculture, and offshore oil and gas exploration, are at risk due to potential hazardous events and dynamic and complex environmental conditions. The technological advances in sensor and signal processing technology, complex algorithms, machine learning systems, powerful processors to execute software, enhance the development of autonomous marine systems (AMS). AMS may reduce the exposure of personnel and hence the risks for human operators (Thieme and Utne 2017, Komianos 2018a, Thieme 2018). Also, AMS may help to improve the efficiency and performance of the human operators, supporting them in decision-making and supervision (Utne et al. 2019).

Today, various types of AMS are applied and developed. For example, in the Nansen Legacy project, unmanned underwater vehicles (UUVs) and unmanned surface vehicles (USVs), are essential tools to collect ecosystem data from the oceans. UUV, also known as an underwater drone, is a typical type of AMS. It is defined as a “self-propelled submersible whose operation is either fully autonomous (preprogrammed or real-time adaptive mission control) or under minimal supervisory control and is untethered except possibly, for data links such as a fiber-optic cable” (Christ and Wernli Sr 2013). They are widely used AMS for scientific, commercial, and military purposes. UUVs mainly consists of two categories: remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs).

ROVs are tethered vehicles. They are normally remotely controlled by a human operator through a tethered cable connected to the surface, while the tether cable provides power and/or communication to the ROV (Christ and Wernli Sr 2013). AUVs are free from a tether. They can operate with varying levels of autonomous capabilities (Watson et al. 2020), e.g., either predefined or adaptive missions. An AUV may operate autonomously without human operators' intervention during the mission (Brito and Griffiths 2016). Their speed, mobility, and spatial range are better than those of ROVs (Wynn et al. 2014). Today, AUVs are commercially available with depths up to 6000 meters, and are able to carry a variety of payload

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[1] https://arvenetternansen.com

sensors relevant to geophysics and oceanography, such as multibeam echosounders, sidescan sonar, and seafloor-imaging tools (Wynn et al. 2014, Norgren 2018). These features make AUV an ideal tool for data-gathering applications in scientific (Dowdeswell et al. 2008, Jenkins et al. 2010), military (Rothrock and Wensnahan 2007), and geopolitical areas (Brito et al. 2012).

Maritime autonomous surface ships (MASS), a general term for autonomous ships (Rødseth; and Nordahl 2017), is described as a “next generation modular control systems and communications technology that will enable wireless monitoring and control functions both on and off the board. These will include advanced decision support systems to provide a capability to operate ships remotely under semi or fully autonomous control” (Kretschmann et al. 2015). They are expected to be used for future maritime transportation of people or goods. The development, application, operational procedure, regulations, and quality assurance standards have been explored in several existing projects, including maritime unmanned navigation through intelligence in networks (MUNIN), ReVolt, and YARA Birkeland (Munim 2019).

USVs are normally of small or medium sizes, with a length of 2 to 15 m and displacements of 1.5 to 10 t (Bertram 2008). Rather than being used for transport, USVs are primarily used for scientific investigations, mines and anti-submarine warfare missions through the payload sensors (Yan et al. 2010). In addition to the missions where the USV is applied alone, the USV is also used as a supporting system or as part of a cooperative mission with other systems, such as USV-AUV system (Norgren et al. 2015, Sarda and Dhanak 2016) and USV-unmanned aerial vehicles (UAVs) system (Sinisterra et al. 2017, Shao et al. 2019).

Safety is of utmost concern in the marine field. Compared to conventional marine systems, AMS will be operated with less human interventions in the future, e.g., with humans in a shore control center (SCC). New types of failures might be introduced due to unforeseen interdependencies in the system design, dynamic operating environments, maintenance challenges, insufficient situation awareness and decision-making from human operators, etc. More importantly, AMS functions are constantly being improved, and the operations with AMS have become more complex and advanced. It is therefore essential to ensure that AMS has a sufficient level of reliability, availability, maintainability and safety to be acceptable for widespread use. For example, MASS should be as safe as conventional ships (Laurinen 2016). With this premise, the following subsection describes the research objectives that underlie this thesis.

1.2 Research objectives

The overall aim of this project of Philosophiae doctor (PhD) is to *develop methods and models for analyzing and controlling safety in operations of autonomous marine systems*. The methods and models proposed in this study are expected to lead to a reduced number of serious incidents, and improved mission success. The research study is decomposed into three main research objectives that are addressed specifically in the papers in Part II.

An important step towards successfully enforcing safety of AMS operations is to understand how and why incidents or accidents may occur. However, the increasing system complexity and advancements in technology makes this process challenging for AMS. This is because that each component or subsystem does not operate independently in AMS operation. In addition to the physical or functional failure of components that have been highlighted in traditional hardware systems, safety challenges are posed by unsafe interactions between physical components, software, human operator, the operating environment, and other AMS. Successful identification of potential hazards/hazardous events in AMS operations can provide a solid foundation for analyzing and controlling its safety.

A risk model is a qualitative or quantitative representation of a system. It can provide information about the risks to decision-makers, including both operators and the AMS itself. To develop a risk model, risk analysis is needed. Numerous hazard identification and risk analysis methods have been proposed in the past decades, such as preliminary hazard analysis (PHA), hazard and operability analysis (HAZOP), and system theoretic process analysis (STPA). These methods use different approaches to identify and analyze potential hazards and therefore have different areas of focus and different ways of presenting the results obtained. With increasing levels of AMS' autonomy and the need to dynamically assess possible risks, it is necessary to identify the gaps in existing methods and investigate the applicability of using their results in developing online risk models for AMS, i.e., the risk models that are able to assess the potential risk dynamically and support the decision-making of the AMS. The strengths and weaknesses of these methods also demonstrate the need for potential additions and modifications.

This leads to the formulation of the first research objective (RO 1):

- **Research Objective 1 (RO 1):** Identify and analyze hazards and hazardous events in the operation of autonomous marine systems and evaluate the applicability of relevant methods as a basis for online risk modeling of autonomous marine systems.

The results of this research objective help provide an appropriate first step towards a general framework for online risk modeling for AMS.

One of the main challenges with respect to the safety of AMS operations arises from its dynamic operating conditions, i.e., operating environment and system status, during the operation. The environmental conditions, traffic situations, technical and organizational conditions are changing continuously during the operation.

The operating environment is one of the factors that seriously affects the safe operation of AMS. For example, MASS may operate in highly congested traffic areas, and UUVs may be used in harsh environments, such as in the Arctic. Also, the operating environment inevitably changes, and should be identified to support human operators of the AMS operations and improve the intelligence of the AMS itself. Additionally, it is critical to analyze the effect of the dynamic environments on AMS operations.

Furthermore, as operations progress, the system status, for example, of a MASS, is largely affected by component degradation and operational management (such as maintenance operations). In contrast to conventional marine systems where the human operators can perform maintenance frequently and flexibly, only a limited number of or no crew will be involved during the voyage. When the operation time is long and the maintenance opportunities are limited, the dynamic change of the system status during the operation and the impact of operational management should be well assessed. An appropriate maintenance plan based on the analysis can be essential to control the safety of the operations. Therefore, Research Objective 2 (RO 2) is thus formulated as:

- **Research Objective 2 (RO 2):** Analyze the dynamic changes in the operating environment and system status, and model their impacts on the safe operation.

Compared to conventional marine systems, AMS need improved perception, situation awareness, and planning/re-planning capabilities due to the reduced number of involved human operators. Considering the potential hazards/ hazardous events and the rapid changes in the operating environment and system status, the risk level involved in the operation may vary greatly and rapidly in time. Hence, risk monitoring and risk control during an operation is decisive for the safe operations of AMS.

The development of wireless technology, cheaper and more advanced sensor technology, and improved computational capability is promoting the development of dynamic and online risk assessment (Vinnem et al. 2015, Zio 2018). Online risk monitoring and risk control of the autonomous vehicles allow for improved situation awareness and early warning of deviations and potentially hazardous events during operation. Hence, an online risk model that is able to analyze the possible risks dynamically and support the decision-making of the AMS is necessary for controlling the safety of AMS operations. Therefore, Research Objective 3 (RO 3) is thus formulated as follows:

- **Research Objective 3 (RO 3):** Propose a general method for developing online risk models for autonomous marine systems and operations, supporting risk-based control.

1.3 Scope and delimitations

There are as mentioned several types of AMS. This thesis mainly focuses on AUV and MASS. Regarding the work related to AUVs, the operational experience and data from the Applied

Underwater Robotics Laboratory (AUR Lab) at Norwegian University of Science and Technology (NTNU) and the information from the literature have been used. The main findings and conclusions from these studies are, however, more or less generic and could thus be adapted to other AMS, as well.

Compared to other types of AMS, the maintenance operations of MASS are more challenging due to more complex dependencies between components and the limited and irregular maintenance opportunities. Therefore, MASS was selected as the research object in the case study related to maintenance planning to highlight the practicality of the proposed method. Even though several studies have been conducted on MASS, insufficient operational experience and reliability/ maintenance data are available. Therefore, assumptions on the operational mode and maintenance strategies had to be made in the work. In addition, due to the lack of data from MASS, the reliability/ maintenance data from conventional ships were used to test the proposed method. Still, a general framework for AMS' dynamic maintenance planning is proposed, which could be adapted to different operational modes, maintenance strategies, and types of components.

USV is involved in this thesis as part of the collaborative USV-AUV system, and results may be transferred to the case of the operation of USV.

The works in this thesis mainly focus on hazardous events that may lead to the loss of or damage to AMS and the failure of missions. This means that consequences, such as injuries to human operators and negative impacts to the environment, are not explicitly addressed in the thesis, even though they may potentially result from loss or damage to AMS and failure of missions. In addition, the thesis mainly focuses on safety in terms of random hazardous events. The consequences caused by intentional human actions or human behavior are not explicitly addressed in the thesis.

1.4 Thesis structure

The thesis is written in the form of a collection of articles, and consists of two main parts. Part I is the main report, which presents the background of the research, introduction to the research objectives, methodology and a synthesis of the contributions from the research presented in articles. Part II contains the articles that form the basis of this thesis.

The main report of the thesis (Part I) is structured as follows:

Section 1 introduces the topic of AMS and the challenges with respect to its safe operation. The research objectives, scope and limitations of the thesis are presented as well.

Section 2 covers the theoretical background for the thesis and state of the art on which the research is based. It starts with some important concepts related to AMS and risk. The system approach to the safety of AMS and the maintenance planning challenges are then discussed in this section. Furthermore, this section provides an overview on the state of the art of risk assessment and analysis for AMS. The concept of and need for an online risk model of AMS are described.

Section 3 summarizes the research methodology and work process.

Section 4 presents the main results from this thesis and describes how the conducted research contributes to addressing the research objectives.

Section 5 concludes the research and recommends future research based on the present the work in the PhD project.

References are included in the last section of Part I.

2 Theoretical Background and State of the Art

2.1 Concepts and terminology

2.1.1 Autonomy and autonomous marine systems

The term “autonomy” is used to describe the system’s “ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned by its human operator(s)” through designed human-machine interface (HMI) (Huang 2004). The degree of this ability can be assessed using levels of autonomy (LoA) (Vagia et al. 2016).

Different scales for LoA have been proposed by previous research (Sheridan and Verplank 1978, Endsley 1987, Sheridan 1992). LoA scales start with low LoA, where it is the responsibility of the human operator to receive information from the system and environment, assess the situation, make decisions, and issue commands to the hardware. When software takes over these tasks, the LoA increases to higher levels. In LoA between lower and higher levels, these tasks are shared between software and humans. It should be noted that an autonomous system may be able to operate in different LoA depending on the situations (Sheridan 2011) or change the LoA during an operation (Yang et al. 2020b). Utne et al. (2017) propose four-level LoAs for generally autonomous systems and operations, as shown in Table 2.1. This scale is well suited for AMS and has been used in the research of AMS (Ludvigsen and Sørensen 2016, Thieme 2018, Ramos et al. 2019b, Ramos et al. 2020, Yang et al. 2020b).

Table 2.1 Levels of autonomous systems and operations. Based on Utne et al. (2017).

LoA	Type of operation	Description
1	Automatic operation (Remote control)	The system operates automatically. The human operator directs and controls all high-level mission planning, often preprogramed. System states, environmental conditions and sensor data are presented to the operator through a human-machine interface (HMI).
2	Management by consent	The system automatically makes recommendations for missions or process actions related to specific functions, and the system prompts the human operator at important points in time for information or decisions. However, the system in this level may have limited bandwidth for communication. The system can perform some tasks independently of human control when delegated to do so.
3	Semi-autonomous operation or management by exception	The system automatically executes mission-related functions when response times are too short for human intervention. The human may override or change parameters and cancel or redirect actions within defined timelines. The operator's attention is only brought to exceptions for certain decisions.
4	Highly autonomous operation	The system automatically executes missions or process related functions in an unstructured environment with the ability to plan and replan the mission or process. The human may be informed about the progress, but the system operates independently and intelligently.

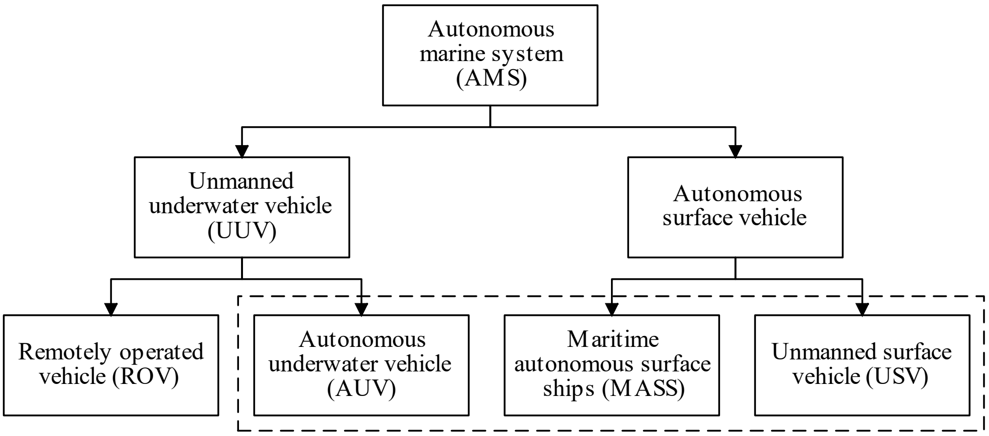

Fig. 2.1 Classification of AMS. Adapted from Rødseth and Nordahl (2017). The dotted box marks the systems that are investigated in this thesis.

An overview of AMS is categorized in Fig. 2.1. The AUVs are mainly located in LoA 2 and LoA 3 of the scale defined in Table 2.1. They usually have their missions with pre-defined paths programmed ahead of the operations (Ludvigsen and Sørensen 2016). During operation, only limited inputs from the human operators are available. In recent years, AUV operations with improved autonomy, such as adaptive sampling, is attracting the attention of researchers. In this case, AUVs have the ability of replanning and may have adaptive paths rather than a pre-defined only, if the payload sensor data are processed aboard as close to real time as possible (ibid.). AUVs can also be controlled remotely, i.e., operating in LoA 1, when sufficient communication is available, e.g., when the AUV is on the surface.

ROVs are typically in LoA 1. ROVs are operated with the connection to the surface using a tethered cable, while the tether cable provides power and/or communication to the ROV (Christ and Wernli Sr 2013). Some attempts have been made to use ROVs in LoA 2 and LoA 3 and operate with dynamic LoA, e.g., autonomous tracking of the aquaculture net pen (Rundtop and Frank 2016, Yang et al. 2020b, Amundsen et al. 2021).

USVs may operate in LoAs 1-3. They can be remotely controlled, and they may have the ability to operate in a higher LoA with onboard payload sensor and processing ability. For example, an USV may operate in LoA 2 or LoA 3 as part of a cooperative mission with other systems, such as USV-AUV system (Norgren et al. 2015, Sarda and Dhanak 2016).

In the case of MASS, it may operate in one of the three modes: conventional and fully manned, remotely controlled or highly autonomous (Burmeister et al. 2014, Bertram 2016). Thieme (2018) summarize three main concepts on MASS that have been proposed: (1) low manned vessels with a partly unattended bridge; (2) a swarm of MASSs supervised by one manned ship; and (3) MASS supervised by SCC. Therefore, LoA of MASS may vary depending on the different MASS concepts.

In general, most AMS are currently in LoA 1-3, and highly autonomous systems are still under development.

2.1.2 Risk, safety, and related concepts

The definition of the term "risk" has been discussed in the literature, and there is no agreed definition of the concept of risk (Aven 2012). It may be interpreted in different ways depending on the context and topic. In ISO 31000 (2009), risk is defined as "effect of uncertainty on objectives", which can be further expressed as a combination of the consequences of an event and the associated likelihood of occurrence.

Following this, the safety can be defined as "a state where the risk has been reduced to a level that is as low as reasonably practicable (ALARP) and where the remaining risk is generally accepted" (Rausand and Haugen 2020). According to this definition, the safety is a function of risk: "safety is a relative condition that is based on a judgment of the acceptability of risk".

Safety is a state that either is reached or not based on the risk level and its acceptability (ibid). Therefore, risk analysis is essential for analyzing and controlling safety.

Risk is always related to what can happen in the future (Rausand and Haugen 2020). Risk analysis is defined as "systematic use of available information to identify hazards and to estimate the risk to individuals, property, and the environment "(Commission 1995). It answers three questions (Kaplan and Garrick 1981): (1) what can go wrong, (2) what is the likelihood of that happening, and (3) what are the consequences? The results obtained from risk analysis is usually compared with some risk acceptance criteria. This process is called risk evaluation. The overall process of risk analysis and risk evaluation is called risk assessment (Rausand and Haugen 2020). Risk management is "a continuous management process with the objective to identify, analyze, and assess potential hazards in a system or related to an activity and to identify and introduce risk control measures to eliminate or reduce potential harms to people, the environment, or other assets" (Rausand and Haugen 2020). Fig. 2.2 demonstrates the relationship between risk analysis, evaluation, assessment, and management.

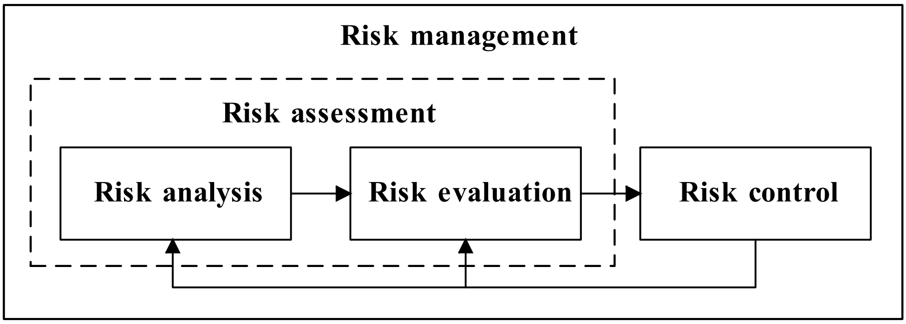

Fig. 2.2 Risk analysis, evaluation, assessment, and management. Reproduced from Rausand and Haugen (2020).

Some other terms that relevant to this thesis are defined as following in accordance with Rausand and Haugen (2020) and Rausand et al. (2021):

Accident is a sudden, unwanted, and unplanned event or event sequence that leads to harm to people, the environment, or other assets.

Hazard is a source of danger that may cause harm to an asset.

Hazardous event is the first event in a sequence of events that, if not controlled, will lead to undesired consequences (harm) to some assets.

Risk influencing factor (RIF) is a relatively stable condition that influences the risk.

Reliability is the ability of an item to perform as required in a stated operating context and for a stated period of time.

Maintenance is the combination of all technical and management actions during the life cycle of an item intended to retain the item in, or restore it to, a state in which it can perform as required.

2.2 A systems approach to safety of AMS

Autonomous systems are embedded with software and high functional dependencies and integration (Chaal et al. 2019). One of the characteristics of autonomous systems is the strong interaction among its different components, which can be difficult to identify and analyze (Utne et al. 2017, Ramos et al. 2019a). This characteristic makes autonomous systems complex systems. During operation, the components involved include hardware, software, and human operators or supervisors. The performance of a single component in the system might be different when it performs separately. Furthermore, their interactions may occur in partially unknown and unpredictable environments (Ramos et al. 2019a). Due to this, new types of failure modes may be introduced. A system approach is therefore essential to the safety of AMS.

In this thesis, STPA is an important tool to analyze the potential accidents and determine the risk influencing factors for developing risk models of AMS operations. STPA is a hazard analysis method mainly based on the idea that safety is controlled by enforcing constraints on the system behavior (Leveson 2011). Instead of considering that an accident is the result of a chain of component or event failures, STPA focuses on the unsafe interaction among the components in a system and that these are the main reason leading to an accident. It is assumed that the hazardous events occur due to the absence, presence, or the improper timing of control actions. Compared to other methods, STPA enables hazard analysis with a wider perspective by considering the wider sociotechnical system to which the technical system belongs.

Several studies have focused on safety and risk aspects through the application of STPA for AMS.

A series of works by Wróbel et al. (2017, 2018a, 2018b) established a possible safety control structure for autonomous ships. A comprehensive hazard identification analysis based on STPA was conducted to provide design recommendations for autonomous ships in terms of regulations, organization, and technology.

Rokseth et al. (2019) presented an approach to derive potential loss scenarios for autonomous ships and associated safety requirements. The analysis results are used to develop a safety verification program aimed at verifying safety. This study provides a practical way of generating a holistic safety verification program for autonomous ships.

Yang et al. (2020b) proposed an adapted STPA method for hazard identification, highlighting the unsafe transitions between different LoA in systems. The proposed method is applied in a ROV with four operational modes with different LoAs.

Chaal et al. (2020) proposed a framework for STPA and a hierarchical control structure for an autonomous ship. The work demonstrates how some human controllers can be replaced by automated controllers as well as the new hazards that these new technologies can introduce. Chaal et al. (2022) proposed a framework to perform risk assessment and select the risk control options of future ships, in which STPA is used for hazard identification and as the qualitative basis for the risk model.

2.3 Maintenance and operational challenges in AMS

One of the most critical issues for the safe operation of AMS is maintaining their reliability during operation (Komianos 2018a, Chang et al. 2021), which requires proper and timely maintenance for all components. For the maintenance of conventional marine systems, taking ship maintenance for example, maintenance activities can be divided into three categories (Deris et al. 1999): (1) on-board maintenance, including regular or routine checks and services that can be carried out by crews every day without disturbing the operations; (2) harbor maintenance, usually the medium-scale maintenance, requiring ships to be anchored at the harbor for maintenance; (3) dockyard maintenance, which is carried out at the dockyard due to the major maintenance work. Well-trained and experienced shipboard personnel are essential to ensure the system's operational availability (Komianos 2018b).

Compared to conventional systems few or even no crew are involved during the operation of AMS (Komianos 2018a). This means that most maintenance and repairs must be carried out at harbors for AMS, which present operational challenges to some AMS, and therefore efficient maintenance planning is decisive to ensure high availability for these systems.

Maintenance planning for multi-component systems has been extensively studied in the last few decades, and apply to various systems. Hence, this subsection summaries the available literature on maintenance planning for multi-component systems in general. It has been claimed that three main dependencies should be considered when planning the maintenance operations for multi-component systems, including economic dependence, structural dependence, and stochastic dependence (Bouvard et al. 2011, Huynh et al. 2014, Dinh et al. 2022, Wang et al. 2022).

A series of research on the maintenance grouping methods dealing with economic dependency have been made (Dekker 1996, Dekker et al. 1996, Dekker et al. 1997, Wildeman et al. 1997, Nicolai and Dekker 2008, Li et al. 2020). In these works, the concept of penalty functions was proposed to describe the costs of moving the execution time of each individual component. The calculation takes into account potential failure costs caused due to reliability changes. This concept enables the calculation of the total maintenance cost when grouping multiple maintenance activities. In addition, to simplify the N-P problem encountered in the grouping process, several reduction theorems were proposed by Wildeman et al. (1997) for the system with large number of components. Instead of using the concept of penalty function, the method proposed by Vatn (2008) explicitly describes the total maintenance cost by integrating the potential failure cost due to low component/ system reliability and the specific preventive maintenance costs. This provides decision-maker with a clearer view of the maintenance cost. These works provide a solid foundation for further research in this field.

Various maintenance constraints, such as limited maintenance teams, availability constraints, and time-limited opportunities, can significantly affect the maintenance plan. Methods and models (Do Van et al. 2013, Vu et al. 2014, Do et al. 2015) have been proposed to solve the challenges posed by various maintenance constraints. In addition to the typical three dependencies mentioned above, a new type of dependence, i.e., geographical dependence, was identified for geographically dispersed production systems, such as offshore wind farms. Nguyen et al. (2019) proposed a dynamic maintenance planning method by combining of the local search genetic algorithm and branch and bound method. Wu et al. (2020) addressed the challenges of the exiting rolling horizon approach for maintenance grouping. In this work, a novel dynamic maintenance strategy based on the actual maintenance history and health information was proposed by extending the conventional rolling horizon approach. While the above-mentioned studies conduct the maintenance plan is based on the age of components, some studies presented maintenance grouping for condition-based maintenance (Bouvard et al. 2011, Do et al. 2019, Shi et al. 2020, Fan et al. 2021b), in which the maintenance is planned, based on the actual conditions of components with The help of degradation monitoring and measurement.

Though including more than one dependency among components can be difficult, some attempts have been made to consider other dependencies together with economic dependence (Van Horenbeek and Pintelon 2013, Vu et al. 2014, Vijayan and Chaturvedi 2020, Dinh et al. 2022, Huynh et al. 2022). For example, Vijayan and Chaturvedi (2020) used Bayesian belief networks (BBNs) to simulate the stochastic dependency among components. The components with high stochastic dependency tend to be grouped for maintenance together. The work by Fan et al. (2021b) also takes the stochastic dependency into consideration in the group maintenance optimization, in which the dependency factor is introduced to describe the increase in the degradation rate for working components. Do et al. (2019) proposed a condition-based maintenance model for two-component systems considering stochastic and economic dependencies, where the degradation rate of each component depends not only on its own state, but also on the states of other components. Linking the criticality of components to the economic dependence for maintenance planning, Vu et al. (2014) provided a novel approach to address both structural and economic dependencies in maintenance planning. The works by Liang and Parlikad (2020) targets multi-system multi-components networks, where the maintenance plan can be improved by sharing the set-up cost at the system-level and grouping downtime at the network-level. The deterioration of the components is modeled as a continuous-time multi-state stochastic process using Markovian model. This allows different types of dependencies at the system level and network level to be considered in the maintenance model.

Most of the aforementioned works provide a general framework of maintenance planning for systems with multiple components, but none focuses on the special needs of the AMS. For example, an essential assumption made in many of these works is that the maintenance operations are accessible at any time, which is unreasonable for AMS due to the lack of human operator/ repair crew during the operation. This makes existing maintenance planning work not feasible to use directly for AMS.

2.4 Risk assessment of AMS

Many previous studies have been devoted to the risk analysis and assessment of AMS. This subsection summarizes the available literature on AMS. Since AUV is primarily used as the research object in the risk analysis and modeling works presented in this thesis, the review mainly focuses on the previous literature on AUV, while briefly reviewing and presenting some publications on ROVs, MASS, and other types of AMS.

In the field of AUV operations, the earliest research on risk analysis focused on technical systems and components. For example, a series of studies have been conducted to provide numerical estimation of the reliability level of AUV operations (Bian et al. 2009b, Bian et al. 2009a, Xu et al. 2013, Aslansefat et al. 2014, Brito 2016, Yu et al. 2017) using probabilistic methods, including fault tree analysis (FTA), event tree analysis (ETA), and bow-tie (BT) analysis. In these works, the system is broken into multiple subsystems, including the propulsion system, communication system, navigation system and power system. The technical failures of components are believed the main factors to cause the system failure. The mechanisms by which they lead to the subsystem failures and thus the overall AUV system failures are analyzed relying on the historical reliability data.

The maturity of AUV technology has prompted a gradual shift to risk analysis for human operators. Thieme et al. (2015a) presented a risk management framework for general UUV. The developed risk model emphasized the need for considering human and organizational factors' impact on risk. To assess the risk of AUV loss and mission aborts caused by human factors, this study proposed a structured approach applying human reliability analysis, FTA, and ETA. The analysis results from the case study identified measures for risk reduction, including improvement and adaptation of maintenance procedures, missions planning, and fault recognition and solving.

Another work by Thieme et al. (2015b) assessed the probability of monitoring success of an AUV operation using a BBN model. The developed model considered two main risk influencing factors on the AUV operation monitoring, namely the state of the human operator and the quality of human machine interface. It was expected to improve operations by clarifying the strength of relationships between risk and human and organizational factors.

A systems-based risk analysis approach for an Antarctic AUV operations was proposed by Loh et al. (2020). The study claimed that applying system dynamics facilitates the modeling of the complex, interrelated, and dynamic systems of AUV operations, and thus enabling a comprehensive analysis of risks for more effective policy recommendations.

Previous studies have shown that different operating environments expose AUV operations to varying degrees of risk. Brito et al. (2008, 2010) proposed a formal process to elicit expert judgment to quantitatively estimate the probability of AUV loss in various environmental conditions, including open water, coastal, sea ice and ice shelf. The Kaplan-Meier Survival model is developed to link the loss probability to the distance that AUV travels in different environments.

Griffiths and Brito (2008) provided a structured Bayesian approach to risk management of AUV operations in the polar regions. Risk was defined as the loss of AUV in combination with its occurrence probability. Focusing on the AUV under-ice operations, the loss of AUV was believed affected by AUV susceptibility and the effectiveness of recovery from sea ice environments. The proposed risk model captured the causal effects of the environment separately on the vehicle and on the ship and combined these to estimate the risk level. Extended from this work, Brito and Griffiths (2016) provided a rigorous procedure for AUV risk management in hazardous environments by integrating frequentist and BBN modeling. More detailed risk influencing factors, such as underwater obstacles, surface conditions, and ice coverage have been included in the BBN model.

Loh et al. (2019) conducted a risk assessment for AUV under-ice missions based on fuzzy set theory. While risk variables are derived from expert judgement and literature review, a set of fuzzy rules are constructed to identify relationship between variables and used to produce estimation of risk level.

The system status and operating environments may change during the operation. Some attempts have been made to simulate such dynamic process using tools such as Markov models. In the works by Brito and Griffiths (2011), a Markov chain model was applied to assess the reliability of AUVs, aiming to capture the different states of the AUV operation. The work identified a total of 11 discrete states that represent operational stages from prelaunch to recovery. Transitions between states in a Markov model represent transitions between identified operational stages. However, these models only reflect changes between operational stages and fail to reflect more detailed changes within those stages.

More studies regarding risk analyses of AUV operations can be found in the review article by Chen et al. (2021).

There are many similarities in the operation of UUVs, e.g., between AUVs and ROVs, and many previous-reviewed works claim that they can be easily adapted for ROV risk analysis. However, several works specifically use ROVs as case studies. Hegde et al. (2016) developed a method for developing collision risk indicators for autonomous remotely operated vehicle (AROV) applications. The proposed collision risk indicators, including time to collision, mean time to collision and mean impact energy, can be used as a planning tool to identify risk prone paths for AROV. Another work by Hegde et al. (2018) proposed a BBN to model the risk in subsea inspection, maintenance, and repair operation using ROVs and AROV. A scenario-based case studies have been applied to verity the proposed method. The results demonstrated its ability to aid to human supervisors in their decision-making processes.

Most of the existing works on the risk analysis of MASS are primarily for conceptual MASS. Wrobel et al. (2016) presented a BBN-based risk model for unmanned ships. The developed risk model considered various aspects of unmanned shipping originating from both design and operational phases of vessel's life. Thieme et al. (2018) reviewed several existing ship risk models and assessed their applicability to MASS. The results demonstrate that, with extra consideration of the aspects of software and control algorithms and human-machine interaction, some existing risk models, might be used as a basis for developing relevant risk models for MASS. Chang et al. (2021) proposed a framework for quantifying the risk involved in the operations of MASS by combining failure mode and effects analysis (FMEA) method, evidential reasoning, and rule-based Bayesian network. The analysis results claimed that "interaction with manned vessels and detection of objects" as well as "cyber-attacks", "human error" and "equipment failure" contribute the most to the overall risk of MASS operations. Other literatures also provide various methods for analyzing and managing risk involved in MASS operations (Rødseth and Tjora 2014, Bolbot et al. 2021, Fan et al. 2021a, Guo et al. 2021, BahooToroody et al. 2022a, BahooToroody et al. 2022b).

2.5 Online risk modeling of AMS

AMS need improved perception, situation awareness, and planning/re-planning capabilities compared to conventional marine systems, due to the reduced number of involved human operators (Liu et al. 2016, Utne et al. 2020). The rapid changes in the operating environment and system status mean that the risk level should be an essential factor that needs to be monitored and considered for system safety control in operation. In other words, a risk model should be able to assess the possible risk dynamically and support the decision-making of the AMS operation.

Many previous works, as mentioned in Section 2.4, have applied FTA, BT, or BBNs for risk analysis and analysis. These methods provide a static risk picture of a system or an operation based on historical data or expert knowledge, failing to capture the dynamic change of the system's risk level.

Dynamic risk assessment (DRA) aims 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" (Khan et al. 2016). A commonly used method in DRA is dynamic Bayesian network (DBN), which is an extended Bayesian method with additional mechanisms to capture the temporal relationship between variables (Murphy and Russell 2002, Amin et al. 2018). The concept of DRA and DBN modeling have been applied in various industries in the past decade to take advantage of updated information (Khakzad et al. 2012, Khakzad et al. 2013, Paltrinieri et al. 2014, Barua et al. 2016, Wang et al. 2017, Baksh et al. 2018, Liu et al. 2021).

Most existing DRA models rely on incident/accident statistics or temporal dependence to update the risk estimation. This means that they must wait until accidents or near misses occur before updating the estimation of the risk level. Also, the statistical data reflects the population characteristics instead of individual state of the target component/ system (Zio 2018). Therefore, these methods may not provide timely support for decision-making during the AMS operation.

Some attempts have been made to make use of condition-monitoring data in risk assessment (Zadakbar et al. 2013, Kim et al. 2015, Zadakbar et al. 2015, Lazakis et al. 2016). These works use a data-based approach for estimating the risk level. Zio (2018) proposed the concept of condition monitoring-based risk assessment (CMBRA). The idea behind this concept is that degradation mechanisms, such as wear, corrosion, fatigue, crack growth, and oxidation, are common causes of accident initiating events and safety barriers failures. Meanwhile, these degradation processes can be monitored through real time data. Therefore, the CMBRA can update the reliability values and the risk estimation before actual failures occur. Zeng and Zio (2018) presented a DRA method, combining both statistical and condition-monitoring data. This allows for the estimation of risk based on data collected during the operation. In the model they developed, statistical data provides the historical information about the system, while condition-monitoring data provides the degradation status of the specific target system and describes system-specific features.

Moradi and Groth (2020) proposed a systematic framework to integrate probabilistic risk assessment (PRA) and prognostics and health management (PHM), addressing the limitations of traditional PRA on handling multi-dimensional condition monitoring data. In the proposed framework, PHM is applied for data handling at the component level while PRA is applied at system-level with emphasis on engineering knowledge and systems logic modeling.

The above-mentioned works mainly focus on the condition of specific components, reflecting the impact of component reliability on the system. In practice, various factors may contribute to the failure of the system. The concept of online risk management was originally proposed by Vinnem et al. (2015), in which the online risk models are built on data from different sources, including historical data, sensors and measurements, and experience data. The online risk models are expected to provide pre-warnings of possible operational deviations and used for timely decision-making, with the help of appropriate data interpretation methods. Though the framework was originally proposed for floating production storage offloading (FPSO), the concept has in recent years gained increased attention in other fields, such as for autonomous systems (Bremnes et al. 2019, Bremnes et al. 2020, Utne et al. 2020, Rothmund et al. 2021, Johansen and Utne 2022).

Utne et al. (2020) outlined a framework for online risk modeling for an autonomous ship, in which the hazard identification is performed using the STPA and the quantification part of risk analysis is handled by a BBN model. An essential step in this work is to convert the static BBN into an online risk model. This means that the variables that requires real-time monitoring should be determined, so that the real-time sensor data is used to measure the observable variables in the developed risk model. The study points out the obtained online risk level should be able to support the system to assess and control risks during the operation autonomously when few or no human operators are involved. For this purpose, the concept of supervisory risk control (SRC) system was proposed, which means that risk management capabilities are incorporated into the control system for autonomous systems to improve the decision-making and intelligence of such systems". The study discusses how online risk models can contribute to develop different types of SRC systems for an autonomous ship.

Johansen and Utne (2022) highlighted the possibility of integrating the STPA analysis within a BN model for the qualitative online risk assessment. In this work, a supervisory risk controller is proposed to demonstrate how the risk information can be integrated in a MASS' control system. The developed SRC system is able to choose the optimal machinery mode, ship operating mode, and speed reference to maintain safe control of a MASS under changing conditions. A scenario-based case study is applied to test the developed model and controller.

Rothmund et al. (2021) proposed a dynamic decision network (DDN) and a decision-making algorithm was developed for an autonomous robotic system executing a series of independent tasks, including inspection, sampling, or intervention. This work utilizes the estimated risk level for higher-level control, focusing on the selection of different operation strategies consisting of one or multiple actions. Applying the proposed method on the inspection operation using a multirotor drone, three strategies are considered: 1) move on to the next task, 2) execute the current task once and then move on to the next task, or 3) execute a maintenance action before attempting task execution once and then moving on.

Bremnes et al. (2019, 2020) proposed a Bayesian approach for online risk modeling of AUV operation, focusing on the vehicle loss caused by potential collision. Several controllable factors, including altitude, vehicle speed, and control strategy, are considered for making the decision about proximity to ice when operating an underwater vehicle. Different from previous works (Utne et al. 2020, Rothmund et al. 2021, Johansen and Utne 2022), the risk model is developed on a checklist based PHA, instead of STPA.

Parhizkar et al. (2022) highlighted the need to develop online risk models and presented a general framework for online risk assessment considering human, software, and hardware interactions in autonomous complex systems. The work focuses more on online risk models for the human operator to improve their decision-making, and not specifically on the development of SRC for AMS itself, even though the latter is mentioned.

Other than the works mentioned above, very few efforts have been made in the field of online risk modeling, especially how the risk information can be used to improve the intelligence of systems in the area of AMS. Furthermore, several development and modeling challenges, such as evidence uncertainty, are ignored by the previous works in online risk modeling. Therefore, further studies and approaches to the online risk modeling and SRC of AMS are needed to improve the safety and intelligence of the AMS, its situation awareness, and decision-making.

2.6 Research challenges and gaps in analyzing and controlling the safety of AMS operations

In general, the following research challenges and gaps in terms of analyzing and controlling the safety of AMS operations are identified:

- New types of hazards and failure modes may be introduced in AMS, especially when multiple systems are involved in the operation. The hazard identification, risk analysis, and risk modeling processes are challenging in AMS operations and need further studies.
- Maintenance planning impacts the safety of AMS operations; however, there is a lack of relevant methods that focus on the special needs and planning challenges of AMS, for example, the often limited and irregular maintenance opportunities.
- Limited works have been conducted focusing on safety issues arising from the harsh and ever-changing operating environments. More dynamic risk models to reflect the changes and impact on the safety of AMS are lacking.
- Limited works has been devoted to the online risk modeling of AMS. How existing methods can be used for developing online risk models for AMS should be addressed.
- How to build online risk models requires further study. A general framework to develop online risk model for AMS is necessary, in particular with respect to the analysis and modeling of risks.
- Some specific challenges in developing online risk models for AMS, such as evidence uncertainty, need to be addressed.
- How the developed online risk model can be used to develop SRC system for controlling safety need further studies.

3 Research Approach

3.1 Research methodology

Research is “the search for knowledge through objective and systematic method of finding solution to a problem” (Kothari 2009). There are three basic types of research, i.e., quantitative, qualitative, and the mixed (Creswell and Creswell 2017). Qualitative research is concerned with qualitative phenomenon, learning from realities in society (Leavy 2014). It is usually driven by gathering empirical date to explore. On the contrary, the quantitative research is applicable to phenomena that can be expressed in terms of quantity (Kothari 2009). This type of research is based on the measurement of variables, and it examines the relationships among them to test objective theories. It should be noted that quantitative and qualitative classifications are not strictly adversarial or dichotomous. Instead, they can be viewed as two different ends on a continuum (Creswell and Creswell 2017). The mixed research can be considered in the middle of this continuum, combining both quantitative and qualitative methods to explore a research problem.

In the current project, the research started from obtaining an overview of the existing methods and models through a literature review. Given the knowledge of the relevant methods, the research was conducted to identify the potential hazards/ hazardous events in the AMS operation and to analyze the appropriate methods for online risk models for AMS. Based on the identified information and the analysis results, the structures of the risk models were developed. These works are purely qualitative. With these qualitative results, further analyses were carried out in a quantitative manner, for example, the quantification of the developed risk models using BBN or DBN and the quantification of the total maintenance costs through the developed maintenance model. Therefore, the entire PhD project can be considered as mixed research, combining quantitative and qualitative methods.

In addition to the above-mentioned classification of research, Kothari (2009) presents a wide variety of basic types of research:

- Descriptive and analytical research. Descriptive research aims at describing the current state of an object/ system. The researchers only report the objective observation without any control over the variables. On the contrary, in analytical research, a researcher is expected to perform analysis on a specific topic/ system based on the existing information or facts. A conclusion might be made according to the evaluation results. This thesis is a mixture of descriptive and analytical research. For example, the hazard identification and identifying different types of operating environments of AMS are descriptive, and the processes of development of risk model and maintenance model are analytical.

- Applied and fundamental research. Applied research aims at providing a practical solution for a concrete problem exists in the society or industry. Fundamental research, also called basic or pure research, defined as "gathering knowledge for knowledge's sake". It aims to find information that "has a broad base of application". The research objective of this thesis to develop methods and models for analyzing and controlling safety in operations of AMS, applying knowledge to solve a concrete problem in the marine industry. A new method, e.g., maintenance planning method, has been proposed in this thesis to address concrete research challenges in AMS operations. Existing and proposed methods have been tested and used to develop new models, e.g., risk models, for case studies with specific scenarios. Thus, this PhD project can be considered to belong to applied research.

- Conceptual and empirical research. Conceptual research is related to some abstract ideas or theories. It is conducted when new concepts need to be developed or any to existing concepts need to be reinterpreted. Empirical research is data-based research, and its conclusion is obtained through experience or observation alone. Empirical research processes are often conducted without due regard to systems and theories. This thesis is mainly conceptual, working with various concepts in the area of safety and risk engineering. Also, the experience of field trips with AMS operations revealed several safety issues, which contributed to the hazard identification process and the development of risk models.

- Field-setting research or laboratory research or simulation research. Depending on the environment in which the research is to be carried out, it can be classified as field-setting research or laboratory research or simulation research. In this project, many simulations are performed to test the proposed models and explore specific problems associated with them. Also, the author has participated in several field trips with AMS operations. For example, the field trip to the North Barents Sea with the research vessel Kronprins Haakon from November 2019 to December 2019, in which the AUV and ROV were operated in open water and under ice, respectively. These field trips provided the author with first-hand knowledge of AMS operations and information on possible safety challenges. The information and experience contributed to parts of the research in the thesis. None of the work was conducted through laboratory research.

In general, the type of research in this thesis is a mixture of mixed (quantitative and qualitative), descriptive, analytical, applied, conceptual, and simulation-based research. Table 3.1 summarizes the type of research employed in the articles enclosed in this thesis. Detailed information of the specific methodology used in each article is presented in Section 4.1.

Table 3.1 Overview of type of research employed in the articles enclosed in this thesis.

Research type	Article 1	Article 2	Article 3	Article 4	Article 5
Qualitative	Yes	Yes	No	No	No
Quantitative	No	No	No	Yes	No
Mixed	No	No	Yes	No	Yes
Descriptive	Yes	Yes	Yes	No	No
Analytical	No	Yes	Yes	Yes	Yes
Applied	Yes	Yes	Yes	Yes	Yes
Fundamental	No	No	No	No	No
Conceptual	Yes	Yes	Yes	Yes	Yes
Empirical	Yes	Yes	No	No	No
Field-setting research	No	Yes	No	No	No
Laboratory	No	No	No	No	No
Simulation	No	No	Yes	Yes	Yes

3.2 Research work process

The research process in the PhD project can be divided into three main phases, i.e., development of the research plan, PhD study and research articles, and research summary. Fig. 3.1 demonstrates the activities during the research phases. Arrows indicate the interaction between different phases or activities within each phase.

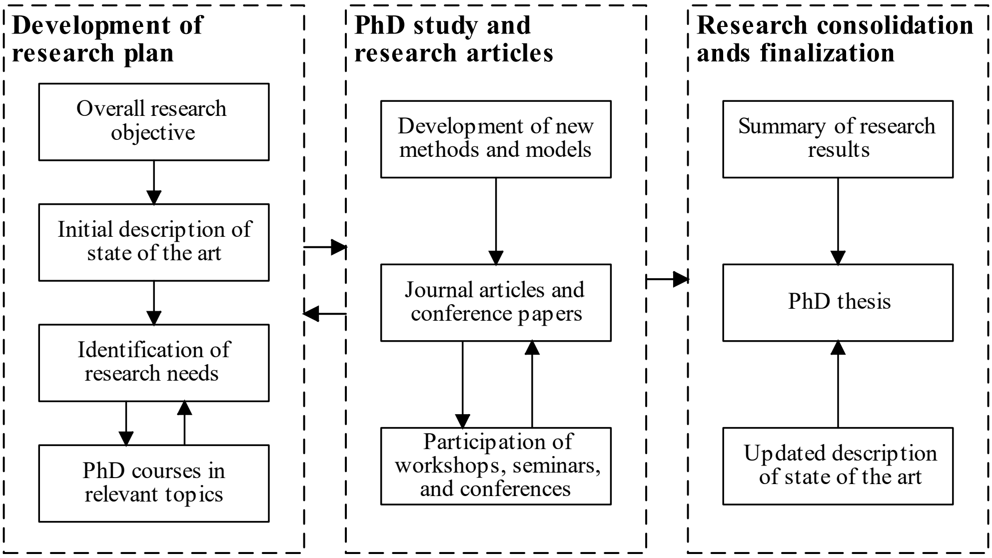

Fig. 3.1 Overall process of the PhD research project.

The research started with the development of the research plan. The overall research objective was initially defined, forming the basis for the whole research work. An initial review of state of the art was conducted to obtain an overview of the safety challenges of AMS operations and existing methods and models applied in this area. Participation in several field trips with AMS operations, including the field trip to the North Barents Sea with the research vessel Kronprins Haakon, provided the author with practical information and experience on the possible safety challenges. It was also essential to obtain an overview of the general state of the art of the risk-related works in other industries. The knowledge gaps and research challenges summarized in this step helped to identify research needs and detailed research objectives to achieve the overall research objective. Examples may include the advantages and shortcomings of applying existing methods and models in the AMS operations or the research gaps that should be further analyzed. These formed the basis for identifying the courses that were taken to fulfill the requirement for attaining a PhD degree at NTNU. Four courses were selected and taken during the PhD study. The topic includes different aspects in the research area of safety, risk, reliability, and maintenance. These courses provided the author with a solid theoretical basis for conducting the research. The contents in the courses also help identify the research needs, in addition to the literature review.

The research objectives were addressed in several research articles in the project. This was mainly achieved by developing new theoretical methods and models for specific research problems. Presentations of the research results and attending workshops, seminars, and conferences received comments and suggestions from experienced researchers and AUV and USV operators. These comments and suggestions have been valuable and, in turn, improved the developed methods/ models and articles. Similarly, developing a research plan and conducting research was an iterative process. New ideas and research needs sometimes were found while conducting research, which in turn updated the research plan. This has been highlighted in Fig. 3.1.

In the third phase, the research results have been summarized and concluded through this thesis. The contributions of the articles to the research objectives are highlighted in the thesis. In addition, the state of the art was updated. This forms the section of theoretical background and state of the art in this thesis.

3.3 Quality assurance

In general, the quality of the research in the thesis has been firstly tested via critical reviews from the supervisors, co-authors, and experienced colleague researchers from this research area. The research quality was further tested through peer review in international journals. In addition, the author has presented parts of the research in workshops and international conferences after undergoing review for acceptance. Direct feedback from reviewers has provided valuable comments and suggestions to improve the quality of the research.

Several brainstorming workshops that gathered people from different fields of expertise, i.e., risk assessment and AUV operation provide valuable input to the analysis results in this thesis. Practical experience and data from previous experiments and operations with AMS from NTNU AUR Lab have been used during the analysis, especially from a research cruise to the North Barents Sea with research vessel Kronprins Haakon. Previous operations provided field experience on environmental conditions and the challenges of AMS operations, including underwater navigation challenges, technical and operational failures, and logistical challenges.

4 Main Results and Contributions

4.1 Main results of each article

This subsection summarizes the purpose, methodology, and main results obtained from all articles in the thesis. The contributions of these works on addressing ROs are presented in Section 4.2.

4.1.1 Article 1 – A system-theoretic approach to hazard identification of operation with multiple autonomous marine systems (AMS)

Purpose and novelty

With multiple AMS working collaboratively, some traditional challenges associated with single AMS operations may be relieved by the presence of a second AMS. Taking the operation of an AUV, for example, the limited survey area can be improved by the presence of a second vehicle. The article presents a case study of an integrated USV-AUVs system operates in coastal areas, with the purpose of ocean monitoring. However, the operation of multiple AMS may bring new challenges, possibly caused by the unsafe interaction between the participating AMS.

The main purpose of Article 1 is to investigate the potential hazards during the operation with multiple AMS and how these hazards may affect the safe and reliable operations of AMS. The novelty of this work is the identification of new challenges brought by multiple participating AMS, highlighting the unsafe interactions between the systems. These safety issues are not well considered and addressed in previous works in the field of risk assessment of AMS operations.

Methodology

STPA was selected and used in this study for hazard identification due to the focus on system interactions, which is feasible for multiple vehicle operation. Fig. 4.1 presents the steps of generic STPA method used in the article.

The definition the purpose of the analysis includes the system to be analyzed, as well as the analysis boundary. This step includes identifying system loss, system-level hazards, and so on. In Step 2, a hierarchical control structure of the system to be analyzed is developed, where the interactions between the components are represented by control actions and feedback. In STPA, unsafe interaction among the components in a system is believed to be the main reason leading to an accident. For each control actions defined in the control structure, unsafe control actions (UCA) that violate the safety constraints and causes the system-level hazards are identified in Step 3. In Step 4, loss scenarios in which UCA may occur are developed and their causal factors are also identified in this step.

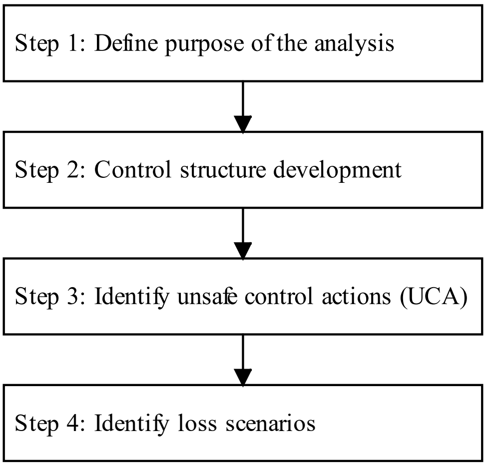

Fig. 4.1 Steps of generic STPA method used in the article.

Results and discussion

A hierarchical control structure diagram was developed in this study, as shown in Fig. 4.2. It illustrates the main components/ subsystems involved in the system, including human operators, USV and multiple AUVs, and the main interactions between them. Given the identified control actions and feedbacks, this control structure is used for identifying UCAs and corresponding loss scenarios and causal factors.

Considering that the difficulties of AUV navigation and the communication between USV and AUV in the case study, the UCA18-N-1 (*Navigation system module in USV does not provide AUV#1 position (Ultra-short baseline (USBL) update) to AUV#1 when AUV#1 is operating under water)* is analyzed in detail in the article. It is found that UCA can occur due to various reasons, including the failure of physical component, software failure in guidance module, inappropriate mission plan by human operators, bad weather conditions, unexpected performance of other AMS, and unexpected environment restrictions on AMS. These are usually unsafe interactions between AMS and environment, between AMS and other AMS, and between AMS and human operators. They may lead to several losses: (1) loss of or damage to AUVs or USV, (2) failure of mission (loss of data, failure to inspect pipeline, etc., and (3) loss of or damage to third-party assets. Therefore, these unsafe interactions can be crucial to the safe operation of multiple AMS, and they should be fully considered and resolved before and during the operation.

The analysis results provide input to improved design of AMS and are expected to support future operations planning with multiple AMS and increase operators’ awareness.

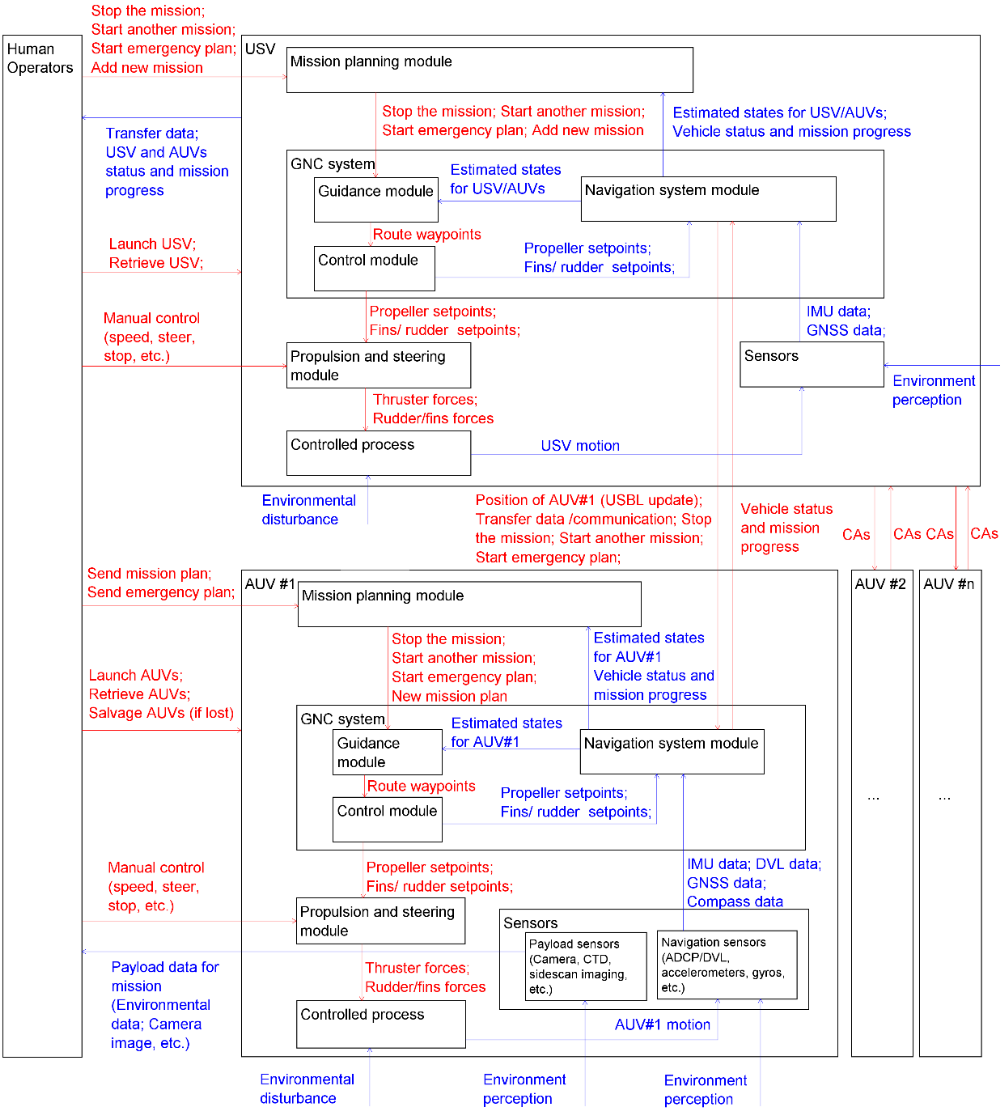

Fig. 4.2 Hierarchical control structure diagram for integrated USV-AUVs operation (Yang et al. 2022b).

4.1.2 Article 2 – Towards an online risk model for autonomous marine systems (AMS)

Purpose and novelty

Considering that few or no human operators are directly involved in the operation of AMS, an online risk model is necessary to enhance the intelligence of the AMS, its situation awareness, and decision-making.

The main purpose of Article 2 is to analyze the applicability of different existing risk analysis methods, i.e., PHA, STPA, and procedural HAZOP, to the online risk modeling of AMS. The novelties of this article are 1) the current study identifies the criteria for an online risk model for AMS, which can be used to assess its validity and effectiveness; 2) advantages and disadvantages of each risk analysis method over the identified criteria are analyzed through the analysis results from a case study; and 3) appropriate methods based on the analysis result are determined, and the information from each method that can be utilized to further develop an online risk model is also identified.

Methodology

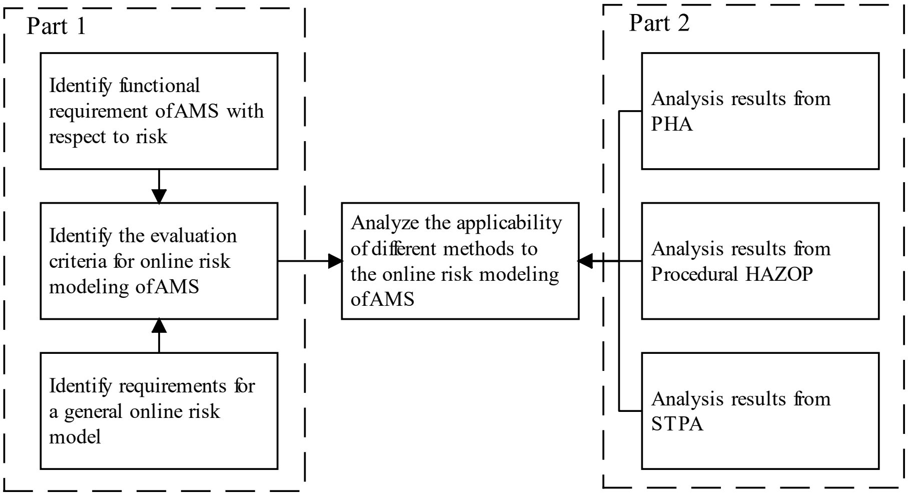

Fig. 4.3 Main steps to analyze the applicability of different methods to the online risk modeling of AMS.

Fig. 4.3 illustrates the method to analyze the applicability of different methods to the online risk modeling of AMS. In the first part, the functional requirements for AMS with respect to risk and online risk models are described. The requirements identified are then used to derive the evaluation criteria for an online risk model for AMS, which are shown in Table 4.1. The identified evaluation criteria demonstrate the potential gaps and focus areas that need to be especially addressed when developing online risk models for AMS. In this article, it is used to assess the efficiency of existing risk methods as a basis for such models.

Table 4.1 Evaluation criteria for online risk modeling of AMS. Adapted from Yang and Utne (2022).

Identifier	Criteria for online risk modeling of AMS
C1	Inclusion of maintenance and reliability aspects of system performance
C2	Inclusion of the performance of software and control algorithm
C3	Inclusion of the performance of the interaction between software and hardware
C4	Inclusion of the performance of the interaction between AMS and external supporting system
C5	Inclusion of the performance of the communication between AMS and environment
C6	Inclusion of the hazards and possible changes in risk models caused by adaptive autonomy/mode or the change of involved subsystems
C7	Inclusion of human–machine interaction
C8	Inclusion of security issues
C9	Inclusion of various sources of data to estimate the risk level, especially sensor data
C10	Level of knowledge (in both the studied system and risk) needed for analysis
C11	Be able to update risk level with new information/data
C12	Be able to deal with emerging risk (the way that the model is changed and/or updated with new data)
C13	Be able to efficiently identify RIFs that need to be monitored online or in real time during operation
C14	Be able to effectively model the correlation among identified RIFs
C15	Be able to deal with the uncertainty, especially the uncertainty from the sensor and real-time data or the data fusion algorithm

In the second part, an AUV under-ice operation in the Arctic was analyzed as a case study using PHA, procedural HAZOP, and STPA. The PHA and procedural HAZOP analysis were conducted through several brainstorming workshops, which gathered people from different fields of expertise, namely risk assessment and AUV operation. The STPA analysis was initially performed by the first author and then reviewed and revised by the same analysts as in PHA and procedural HAZOP workshops. With different advantages/disadvantages and focus areas, the three methods demonstrate different results in hazard identification and risk analysis.

Given the identified evaluation criteria for an online risk model for AMS and the analysis results from three methods, applicability of using these results in online risk modeling of AMS are analyzed by investigating how they contribute to fulfilling each evaluation criteria for online risk modeling of AMS, and how the results may be used as the basis for model development.

Results and discussion

a. Main risks and implications for improved engineering design, operational procedures, and further research

The results of the hazard identification and risk analysis in this article can help designers and operators improve the safety and robustness of AMS operations in the Arctic in the future.

Firstly, compared to the conventional AUV operation, more severe consequences might occur if there is any failure of the physical components in the AUV or supporting systems. From the perspective of engineering design, more reliable and robust physical components are required in the operation of AUVs in the Arctic. Also, adequate testing and verification of the components' reliability in various operating environment before operation and a more effective fail-to-safe mechanism are necessary for a safer operation.

In addition, the analysis results show that the issues related to software or control algorithm may contribute most uncertainty and unexpected hazardous events. These may lead to the loss of the AUV. Therefore, before the actual operation, designers and operators may need focus more on this type of hazard/ hazardous events. For example, a more robust software or control algorithm is required. Also, testing and verification of all onboard software should be performed to ensure quality of software application and design.

Hazards in operational procedures will still have a great importance to the safety of AMS operation, even though human operators are not directly involved and have little control of the vehicle during the operation phase of AUV mission. The related hazards can be caused by inadequate system design, defective software development, insufficient preparation and testing, improper operation steps and behaviors, limited work schedule, etc. Adequate preparation for environmental and operational challenges are necessary for AMS operations in the Arctic.

b. Applicability of using the results in online risk modeling of AMS

In terms of the applicability of using the results in online risk modeling of AMS, Table 4.2 summarizes the main findings from the analysis results.

Table 4.2 Applicability of different methods to the online risk modeling of AMS (Yang and Utne 2022).

Abbreviations: Y-Yes, N-No, P-Partial, I.I.-Insufficient information, L-Low, H-High

Criteria	PHA	Procedural HAZOP	STPA
C1	Y	P	Y
C2	P	P	Y
C3	I.I.	I.I.	I.I.
C4	Y	P	Y
C5	Y	Y	Y
C6	I.I.	I.I.	Y
C7	P	Y	Y
C8	P	P	Y
C9	N	N	N
C10	L	L	H
C11	N	N	N
C12	P	P	P
C13	Y	Y	Y
C14	N	N	N
C15	N	N	N

In general, compared to the other two methods, STPA shows better applicability in terms of the number of criteria fulfilled and thus has the potential to be used as a basis for developing online risk models. Specifically, STPA can provide a more detailed analysis in terms of the issues caused by software and control algorithms, which are considered important factors in most uncertainties and unexpected hazardous events in AMS operations. Furthermore, its ability to visualize the interactions between the AMS and external system using a hierarchical control structure is a valuable contribution to the analysis. This highlights the potential unsafe interactions in the operation, which might pose more problems in the operation of AMS than conventional marine systems. However, STPA provides a list of hazardous events without any ranking or quantification of the risk. This presents challenges when developing online risk models from them, as it becomes difficult to determine which RIFs should be selected for inclusion in the model.

With relatively low knowledge and experience level required, the results from PHA can provide a good understanding of the system. For example, it performs well when analyzing the issues related to reliability and maintenance aspects. Furthermore, it provides a clearer view of environmental impact by explicitly considering the impact of various environmental factors, which makes it the preferred method when harsh environments are considered a major contributor to safe operation. In addition, its semi-quantitative results allow analysts to rank the importance of identified hazardous events, making it easier to determine which RIFs to include when developing online risk models. However, some challenges, such as its ability to software-related failures, handle adaptive autonomy, and security issues makes it difficult to become an ideal online risk modeling method.

The behavior of procedural HAZOP is unsatisfactory in terms of the number of evaluation criteria, especially its ability to deal with reliability-related issues, software-related issues, adaptive autonomy, and security issues. However, the method highlights the issues related to human operators, including the environmental impact and the human-machine interaction. It provides an in-depth analysis result in this area. Many important issues are not covered by the other two methods, which makes procedural HAZOP an excellent complement to them.

In conclusion, STPA is considered a good basis for developing an online risk model while PHA and procedural HAZOP might be used as complementary tools to STPA to address its difficulties in determining the RIFs that should be included in online risk model and identifying specific RIFs that are related to human operators in the AMS operation.

4.1.3 Article 3 – Dynamic risk analysis of operation of the autonomous underwater vehicle (AUV)

Purpose and novelty

The operating environment is one of the factors that seriously affects the safe operation of AUV. In long-range AUV missions, unavoidable changes in the operating environment impact the vehicle risk.

The current work aims to provide a method for assessing the risk of AUV operation, considering the effect of changes in the operating environment. Given the online information of the AUV´s operating environment, a dynamic risk value is evaluated using DBN model. The novelties of this article are that 1) potential operating environments of AUVs and the potential critical environmental factors are determined; 2) the environmental effect on AUV is captured using BBN, and 3) the dynamic change of operating environment are captured using a proposed DBN model, with the help of online location information.

Methodology

Fig. 4.4 illustrates the main step of dynamic risk analysis of the operation of AUV, considering the dynamic change of the operating environment. Given a specific AUV mission, the type and the characteristics of AUV need to be determined. Also, given the planned mission path, the types of potential environments that an AUV might experience along the path can be determined in Step 1. This is followed by determining critical environmental factors that might affect AUV operation in each type of environment in Step 2.

During an AUV mission, real-time location information can be obtained, either by the navigation systems on AUVs or by prediction through the pre-defined path. With this information, the operating environment of the AUV can be updated accordingly in Step 3. In the case that the location is not updated in time, the operating environment is modeled based on the operating environment in previous steps using DBN. The corresponding influence on AUV is simulated using BBNs in this study. In Step 4, the influence of the operating environment on the AUV subsystems is analyzed and represented by the probabilistic method. This results in different potential consequences estimated in Step 5, affecting the risk of AUV operation.

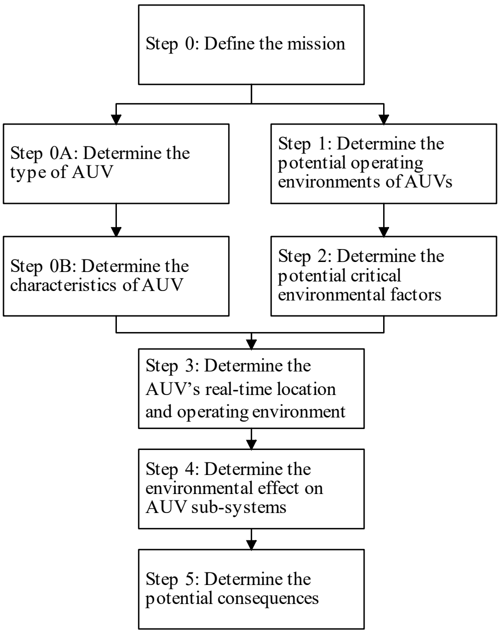

Fig. 4.4 Main steps of dynamic risk analysis of operation of AUV (Yang et al. 2020a).

Results and discussion

In this article, six potential operating environments for an AUV mission in harsh environments were defined. They are open waters, coastal waters, sea ice, ice shelf, islands group, and enclosed environment. For each type of operating environment, critical environmental factors, i.e., environmental factors that have a critical influence on AUV operation, were considered for each type of environment in the risk analysis, as shown in Table 4.3.

Table 4.3 Environmental factors considered for each environment type (Yang et al. 2020a).

	WD	WT	ST	CV	RC	IC	IT	ShT	ES	PF
Open water	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
Coastal	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Sea ice	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No
Ice shelf	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No
Group island	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
Enclosed environment	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No

Abbreviation:

WD = Water Depth, WT = Water Temperature, ST = Seabed Topography, CV = Current Velocity, RC = Rock Concentration, IC = Ice Concentration, IT = Ice Thickness, ShT = Ship Traffic, ES = Engineering Structure, PF = Possible fishing gears

A case study of AUV operation was presented in this paper. Given the estimated location of an AUV during the mission, its operating environment is simulated and predicted using probabilistic method using the DBN. Fig. 4.5 shows the developed DBN for predicting operating environment, environmental effect on AUV subsystems, and the potential consequences.

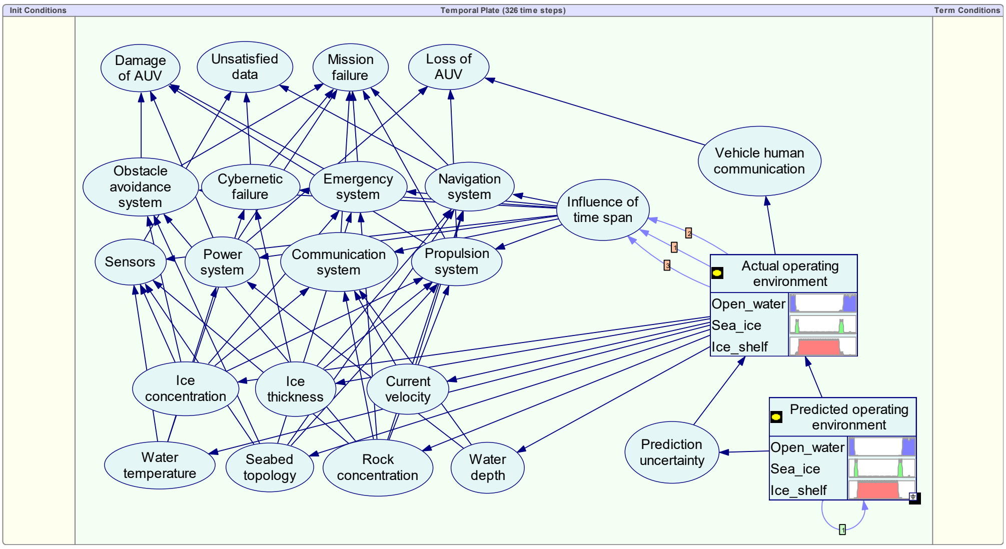

Fig. 4.5 DBN structure of the case study (Yang et al. 2020a).

Fig. 4.6 shows the simulation result of "Damage of AUV" in the case study. The probability of the undesired event changes over time, reflecting the situation of the AUV in different operating environments. In general, the probability of mission failure is relatively high when the vehicle enters the ice region according to the results. This time-varying risk value can serve as a tool to determine the preliminary risk value during the phase of mission planning. Based on this, for example, it can provide is most appropriate path for the AUV mission beforehand by assuming the possible location change of AUV during the mission. During the mission, the developed model provides a clear view of the AUV situation to the human operators. The risk value can serve as an indicator for the AUV operator to monitor the vehicle's status and determine whether a safety plan needs to be taken when the risk value is unacceptably high. In addition, the proposed method provides a quantitative value of risk it can also serve as a risk indicator for the AUV's adaptive mission, which allows AUV to avoid the hazardous environment automatically.

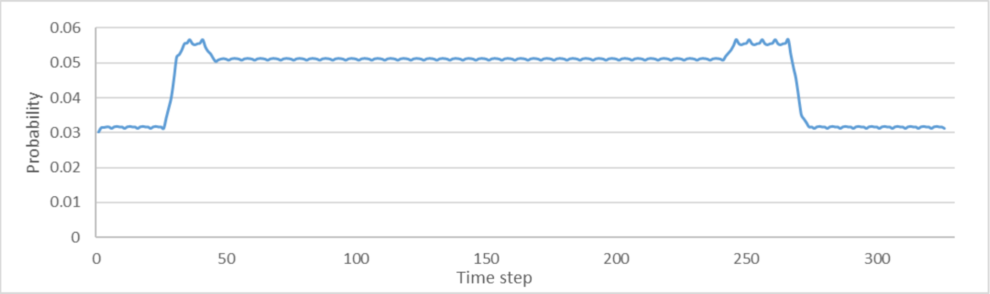

Fig. 4.6 Results of "Damage of AUV" in the risk analysis of the AUV operation (Yang et al. 2020a).

4.1.4 Article 4 – Dynamic maintenance planning for autonomous marine systems (AMS) and operations

Purpose and novelty

Different from the conventional marine systems where the crew onboard can perform maintenance frequently and flexibly, only a limited or no crew will be involved during the voyage of the autonomous systems. This poses challenges for AMS maintenance planning and execution.

The purpose of this article is to propose a dynamic maintenance planning method for AMS, addressing the challenges and research gap of maintenance planning and execution in the field of AMS. The novelties of this article are 1) an applicable group maintenance strategy for AMS is developed by combining a grouping method and a Markov model, considering economic and stochastic dependency among components; 2) a multiphase Markov model is proposed to deal with the potential changes in the maintenance strategies and system states in the context of limited and irregular maintenance opportunities; 3) a long-time perspective is included, which means that the proposed grouping heuristic provides a better maintenance plan in the scenarios with limited and irregular maintenance opportunities, compared to the “short-sighted” methods in previous studies; 4) different types of maintenance strategies for components within the context of AMS in the maintenance planning are considered in the proposed method.

Methodology

Fig. 4.7 demonstrates the framework of the proposed maintenance planning method, consisting of three main parts. In the first part, the problem can be formulated given the maintenance–related information and assumptions and the reliability/ maintenance data. Due to the different strategies of corrective maintenance, two different maintenance models are proposed in Part 2 for the subsystems consisting of only critical components or k-out-of-n (KooN) systems. In KooN system, the structural dependence between components and the load-sharing between components are considered using Markov model. In addition, a multiphase Markov model is proposed to handle the challenges caused by limited and irregular maintenance opportunities and potential different maintenance strategies. In addition, various maintenance strategies of KooN systems within the context of AMS are considered in this study by developing various cost functions.

Given the developed cost functions in Part 2, the total cost for each maintenance grouping and planning strategy can be calculated. For maintenance grouping and optimization, a heuristic is proposed in Part 3.

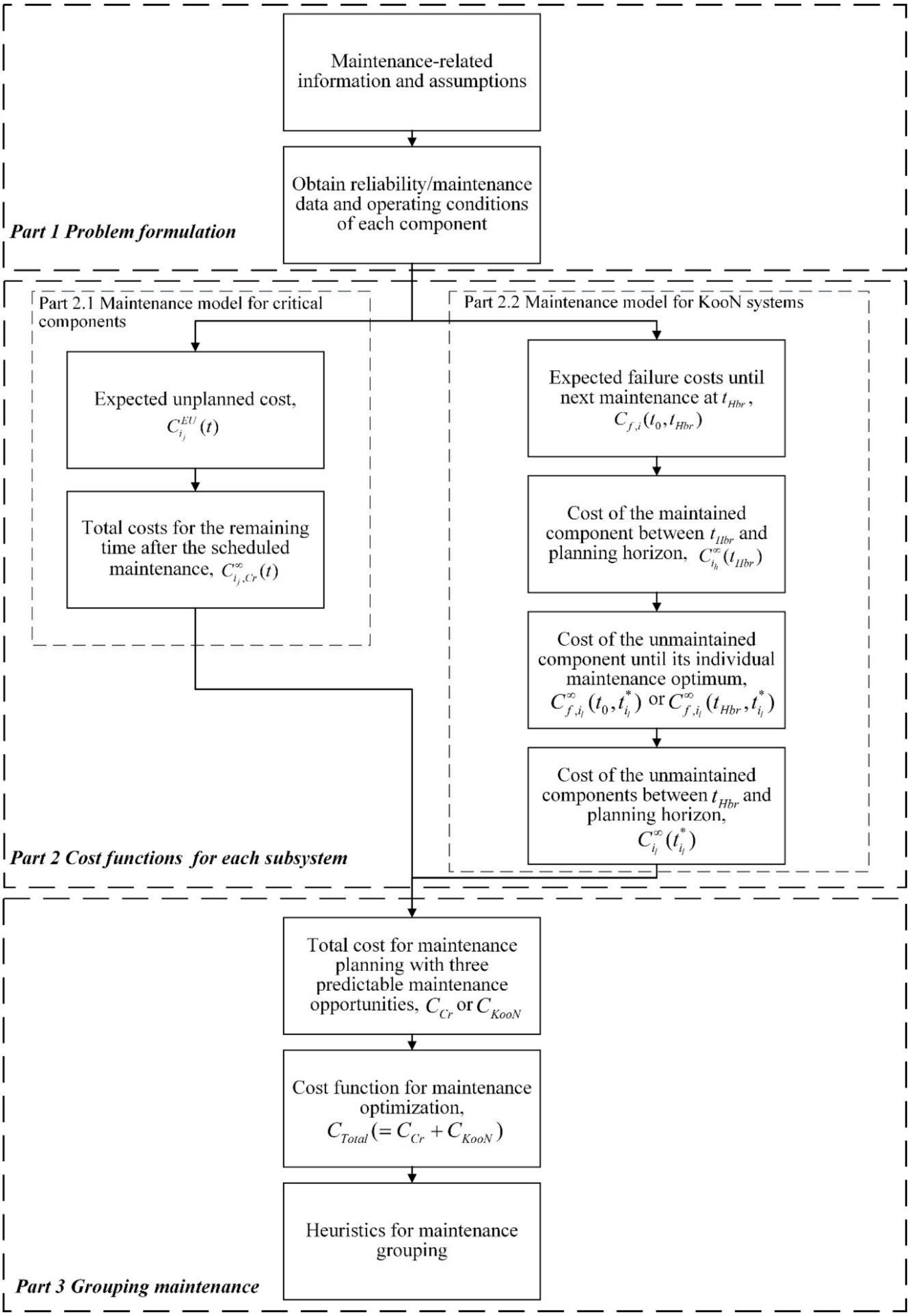

Fig. 4.7 Main steps of the proposed maintenance planning method. Adapted from Yang et al. (2022c).

Results and discussion

A case study of the maintenance of cooling system in an autonomous ship is presented in this article. With three foreseeable maintenance opportunities, 21 components are considered for maintenance planning using the proposed method.

Table 4.4 Maintenance plan according to the proposed method (Yang et al. 2022c).

Id.	Component	Maintenance plan with the proposed planning method	Maintenance plan without considering economic dependence
1_1	HTFW piping	PM: C	PM: A
2_1	HTFW temperature sensor	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait
4_1	HTFW cooler	Wait	Wait
5_1	Expansion tank	PM: C	Wait
6_1	LTFW piping	PM: C	PM: B
7_1	LTFW temperature sensor	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait
9_1	Lubrication oil cooler	PM: C	PM: C
10_1	Main engine charge air cooler	PM: C	PM: B
11_1	Generator cooler	PM: C	PM: C
12_1	Gear oil cooler	PM: C	PM: C
13_1	SW piping	PM: C	PM: C
14_1	HTFW pump 1 (engine driven)	PM: C	PM: C
14_2	HTFW pump 2 (engine driven)	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait
16_1	Central cooler 1	Wait	Wait
16_2	Central cooler 2	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: C	PM: C
17_2	SW pump 2 (electric driven)	Wait	Wait
Total components need to be maintained		10	8
Total maintenance cost (USD)		466969	471981

Note: PM: C represents the preventive maintenance in Harbor C. Wait reprents the components should skip the foreseeable opportunities and wait for future opportunities

Given the assumed maintenance context and data, the maintenance plan is obtained as shown in Table 4.4. The total maintenance cost until the end of the planning horizon is calculated as 4.670×10^5 USD. Without applying the proposed method, each component is assumed to be maintained in its own optimum opportunity, regardless of the economical dependency with other components. In this case, the maintenance cost can be up to 4.720×10^5 USD according to the simulation. The total cost saving by applying the proposed maintenance planning method is 5012 USD, which is 1.06% of the total maintenance cost.

a. Effect of the set-up cost

The set-up costs are the costs required for preparing the maintenance actions, e.g., preparation tasks by maintenance crews, for maintenance tools, and logistics costs. The economic dependencies are principally represented by sharing of the set-up cost in a multi-component system. Fig. 4.8 demonstrates represents the maintenance cost saving as a function of the set-up cost. Both situations that without constraints of maintenance duration are tested. The results show that the proposed method provides relatively high maintenance cost savings, especially when the set-up cost is high. In general, a higher cost saving can be expected when the set-up cost is higher. Special cases occur when the set-up costs are equal to 3000 and 4000 USD are mainly due to the existence of constraint of limited and irregular maintenance opportunities.

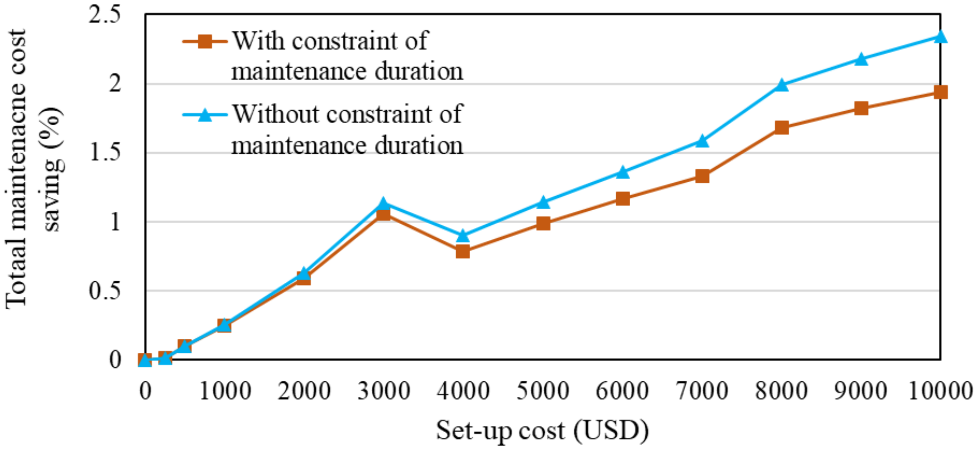

Fig. 4.8 Maintenance cost saving as a function of set-up cost (Yang et al. 2022c).

b. Effect of the grouping horizon in maintenance planning with limited and irregular maintenance opportunities

With the constraints of limited and irregular maintenance opportunities, the previous maintenance grouping methods that consider only the first maintenance opportunity and investigates whether it should be used might be short-sighted. The current work explores the effect of grouping horizon, i.e., the number of considered maintenance opportunities, in the maintenance planning with the constraints of limited and irregular maintenance opportunities.

Table 4.5 shows the comparsion results of the methods with different grouping horizon. It can be found that the proposed method generally performs better than the other two methods (considers one or two maintenance opportunities) and provides lower maintenance costs by considering a longer-term perspective. This is mainly because without the actual information of the future, the “short-sighted” methods provide maintenance plan depending on the assumption of average operating and maintenance conditions. Therefore, they may not provide acceptable maintenance plans when the actual information of future opportunities can be much better or worse than the assumed. For example, better or worse timing for grouping maintenance, or longer or shorter maintenance durations. This issue can be more obvious when maintenance constraints exist, e.g., maintenance duration.

In general, if more information on future opportunities is accessible and used in maintenance planning, the obtained plan can be more economical. A longer grouping horizon, i.e., the proposed method, is highly suggested due to its good performance on cost saving and acceptable simulation time. However, a grouping horizon with more than three maintenance opportunities is not suggested due to the complicated simulation and computation, the reduced gain in terms of cost-saving, and difficulties to obtain information on future maintenance opportunities.

Table 4.5 Maintenance cost of each scenario using methods with different grouping horizon (Yang et al. 2022c).

Scenario Num.	Maintenance duration constraint $[D_{t_A}, D_{t_B}, D_{t_C}]$ (hrs)	Maintenance cost (USD)			Saved cost compared to the method i) (USD)	Saved cost compared to the method ii) (USD)
		i) One harbor	ii) Two harbors	iii) Three harbors		
Scenario 0	[200, 200, 200]	468608	468608	466969	1639	1639
	[200, 200, 50]	468608	468608	467933	675	675
	[200, 200, 350]	468608	468608	466628	1980	1980
Scenario 1	[200, 200, 200]	471155	470120	470120	1035	0
	[200, 200, 50]	471155	470120	470120	1035	0
	[200, 200, 350]	471155	470120	470120	1035	0
Scenario 2	[200, 200, 200]	470788	469756	469756	1032	0
	[200, 200, 50]	470788	469756	469756	1032	0
	[200, 200, 350]	470788	469756	469756	1032	0
Scenario 3	[200, 200, 200]	465858	465858	465858	0	0
	[200, 200, 50]	469627	467021	467021	2606	0
	[200, 200, 350]	465569	465569	465569	0	0

4.1.5 Article 5 – Online risk modeling of autonomous marine system: a case study of autonomous under-ice operation

Purpose and novelty

An online risk model may contribute to enhancing the safety, intelligence of the AMS, its situation awareness, and decision-making. The purpose of this work is to propose a complete framework for the online risk modeling to be implemented in SRC for AMS. The novelties of this article are 1) a new framework for developing online risk models and SRC AMS, addressing some of the existing research gaps in the risk modeling of AMS; 2) evidence uncertainty in online risk modeling is considered and solved using fuzzy set theory; 3) a two-level SRC strategy is proposed for AMS based on online risk level.

Methodology

The proposed framework for developing online risk model and SRC system for AMS is demonstrated in Fig. 4.9. Given the conclusion in Article 2 that STPA can be considered a good basis for developing online risk models for AMS compared toother methods (Yang and Utne 2022), it was selected and used for hazard identification and analysis in Step 1. The top-down demonstration of STPA results is transformed and represented using BBN in Step 2. This determines the preliminary causal relationship between nodes in the developed risk model. Online risk models rely on real-time data from sensor systems to measure and update the risk level. An observation from sensor systems and its evidence uncertainty may cause information loss and thus weaken the ability of the developed risk model. To solve this problem, in Step 3, observations on the continuous variables are converted to probabilistic evidence on the monitored variables by fuzzy discretization. Given the estimated online risk level, a two-level strategy is proposed to develop an SRC system in the case of AUV operations in Step 4. While the low-level SRC is designed to provide AMS with reasonable utility where risk is involved but acceptable, the high-level SRC aims to aid the AMS in reducing or avoiding the possibility of entering an unacceptable risk level.

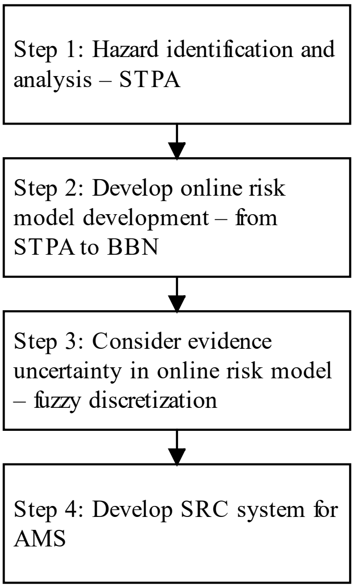

Fig. 4.9 Main steps to develop online risk model and SRC system for AMS.

Results and discussion

The current work presents a case study of an under-ice operation of AUV, while its movement and corresponding data monitoring were established in a simulation environment through MATLAB/Simulink. Following the proposed framework, Fig. 4.10 demonstrates the overall structure of the developed online risk model in the format of an object-oriented Bayesian network (OOBN), highlighting the online input nodes.

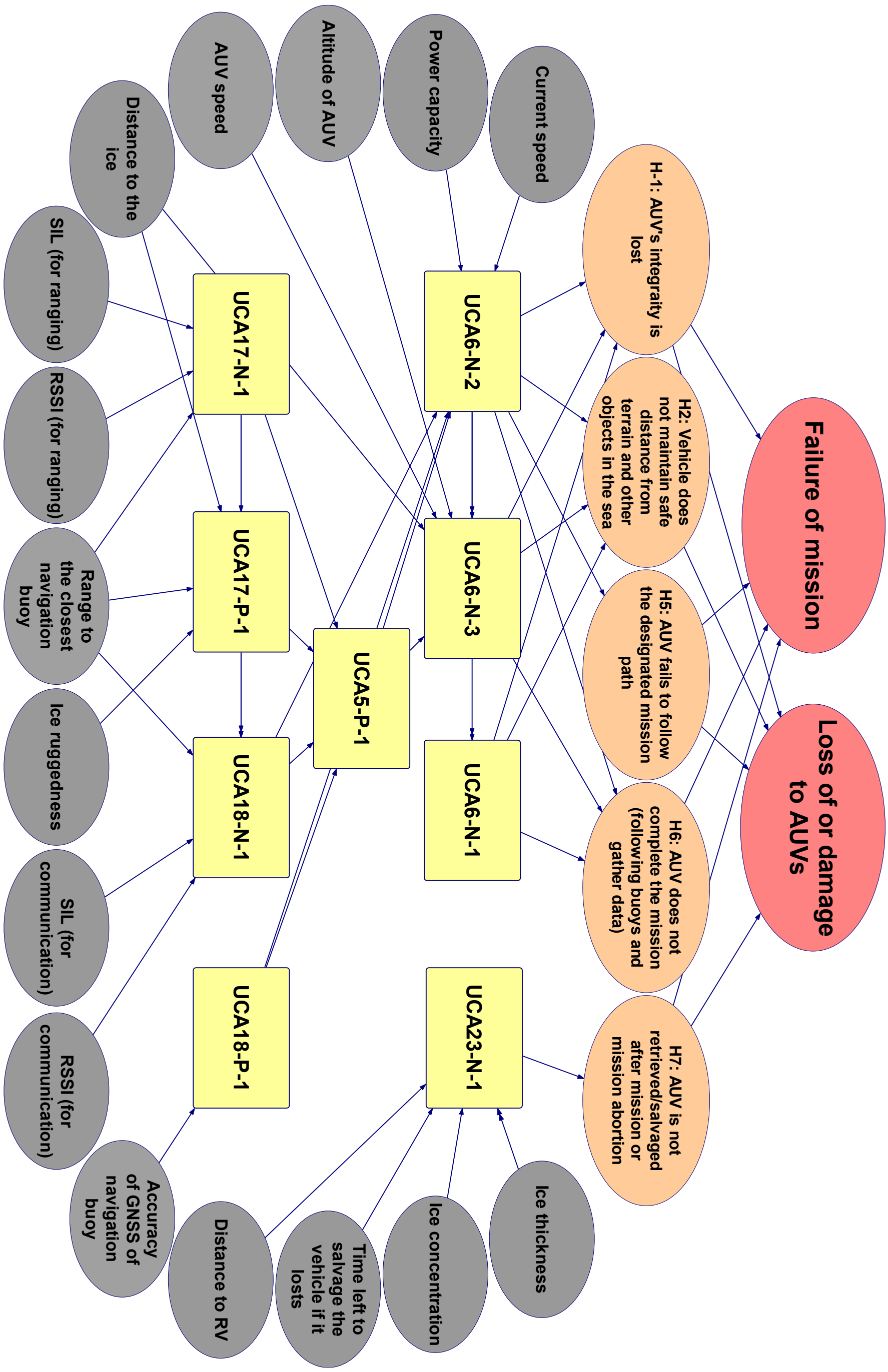

Fig. 4.10 Overall BBN for online risk model, highlighting the values that required for online monitoring by grey color (Yang et al. 2022a).

With the developed online risk model and monitored online input nodes, the probability of "loss of AUV" over the entire mission can be estimated, as shown in Fig. 4.11. The estimated online risk level should be used to support AMS' decision-making during operations.

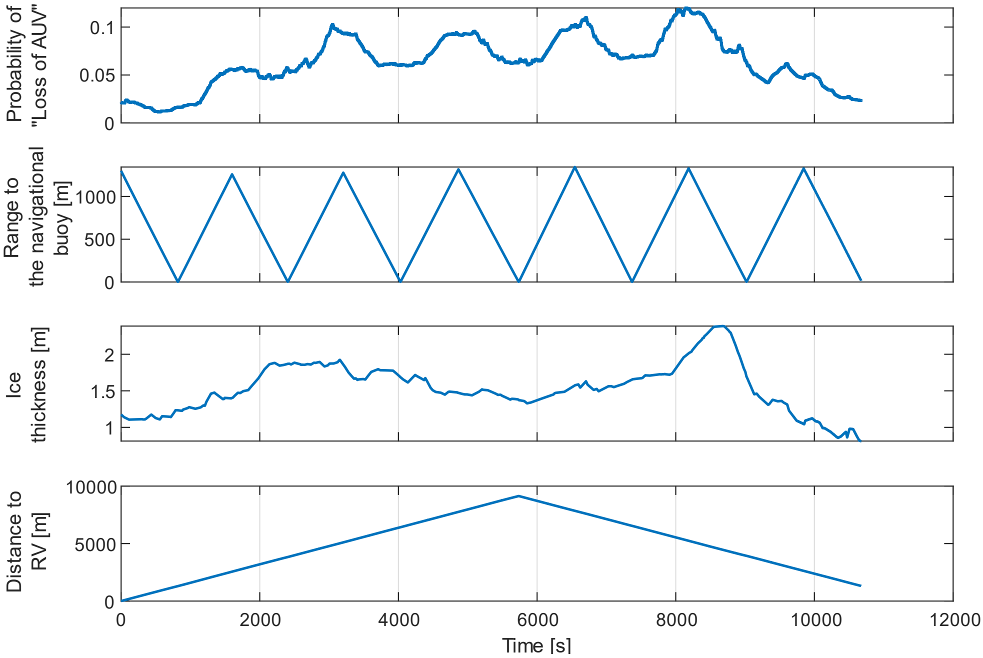

Fig. 4.11 Online risk level and the real-time data of some online input nodes (Yang et al. 2022a).

a. Decision support by the developed online risk model

A low-level SRC was designed to provide AMS with reasonable utility where risk is involved but acceptable. The optimal control strategies are determined by balancing the potential utility it may bring against the potential risk a control strategy may cause.

Generally, when the risk level is relatively low, the developed SRC tends to provide more risky control strategies to gain more utilities. In contrast, when the risk level is relatively high, the developed SRC tends to take more conservative control strategies to make utilities with reasonable corresponding risk.

Fig. 4.12 shows the online risk level and the obtained utilities given the selected control strategies during the operation in the case study. Compared to the operation without the developed low-level SRC, the low-level SRC provides more risky control strategies at the start and the end of the operation by lowering the distance to the ice and increasing the AUV speed. This is to obtain higher levels of potential utility during these periods.

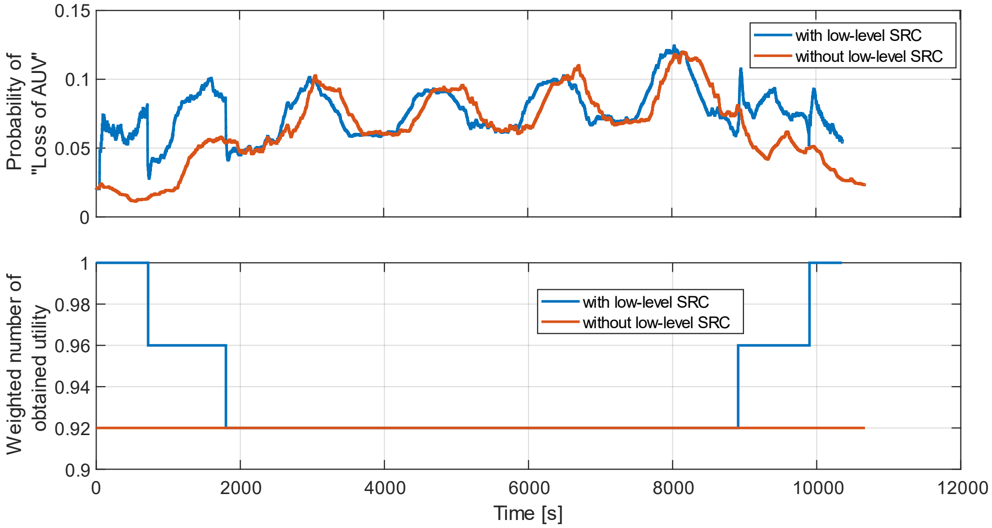

Fig. 4.12 Online risk level and obtained utilities during the operation with and without low-level SRC (Yang et al. 2022a).

In situations where regardless of how the low-level SRC system adjusts the control strategy, the risk level is still deemed unacceptably high for stakeholders, the high-level SRC should activate. In this case, the high-level SRC aborts the mission and starts moving AUV back. Fig. 4.13 shows that with the help of high-level SRC, the unacceptable period, defined as the period that the risk level is above unacceptable level, is limited to last about 130 s. This value is greatly decreased from the operation with only the low-level SRC considered, which is around 2445 s according to the simulation results.

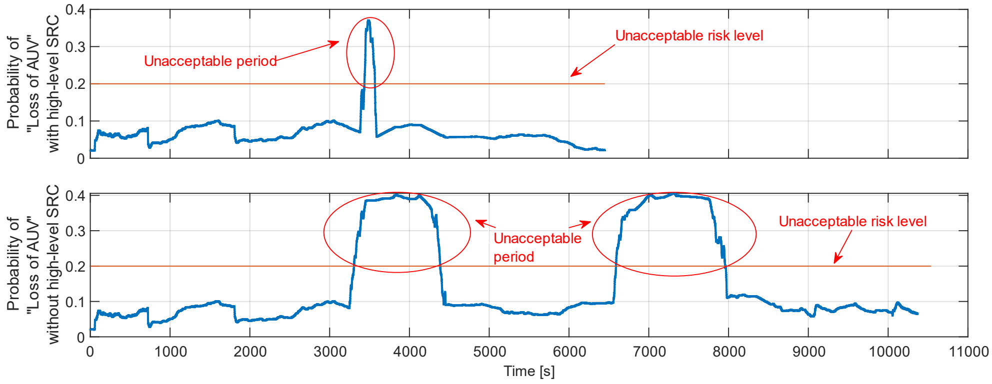

Fig. 4.13 Online risk level with and without high-level SRC (Yang et al. 2022a).

Generally, the developed online risk model and corresponding SRC system SRC can improve the decision-making of the AUV by enabling it to obtain reasonable utility while operating in a relatively benign environment and also be informed if the risk level is unacceptably high.

b. Influence of evidence uncertainty on online risk modeling and SRC

In this study, the influence of evidence uncertainty in the developed online risk model and SRC were investigated and discussed. Fig. 4.14 shows the simulation results of the SRC ignoring the evidence uncertainty, in contrast to the SRC that considers the evidence uncertainty. Firstly, without considering evidence uncertainty, the SRC treats all numerical values in the same state of an online input node equally, which may cause a delay in capturing the change of operating conditions. This can weaken the ability of online risk model to dynamically update the risk level for supporting SRC. In addition, if the evidence uncertainty is ignored, it is possible that even small changes in monitoring values may lead to total changes in the state of the corresponding nodes. This may lead to an unnecessary and unreasonable subsequent change in the control strategies in SRC.

Generally, evidence uncertainty can be influential to the online risk modeling for AMS. It is necessary to be considered and addressed in online risk modeling for AMS.

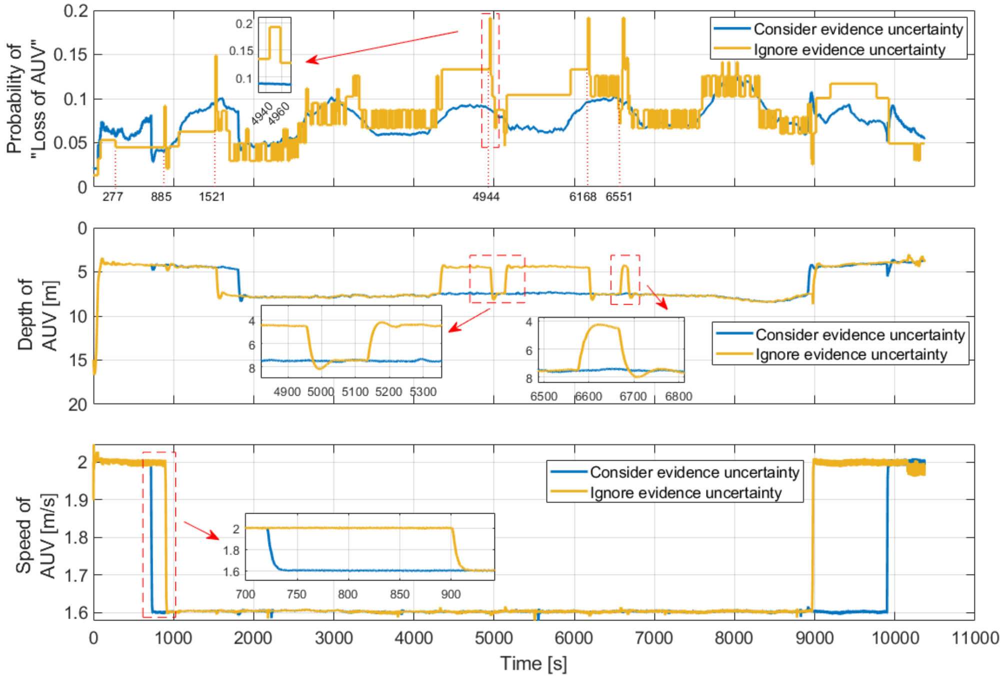

Fig. 4.14 Comparison of simulation results considering and ignoring evidence uncertainty in operations (Yang et al. 2022a).

4.2 Summary of Contributions

This subsection summarizes the contributions from the articles to the research objectives identified in Section 1.2. Fig. 4.15 illustrates the relationship between the overall research objective, research objectives and the research articles included in this thesis. It shows that RO 1 is addressed in Articles 1 and 2; RO 2 is addressed through Articles 3 and 4; RO 3 is addressed through Articles 2 and 5.

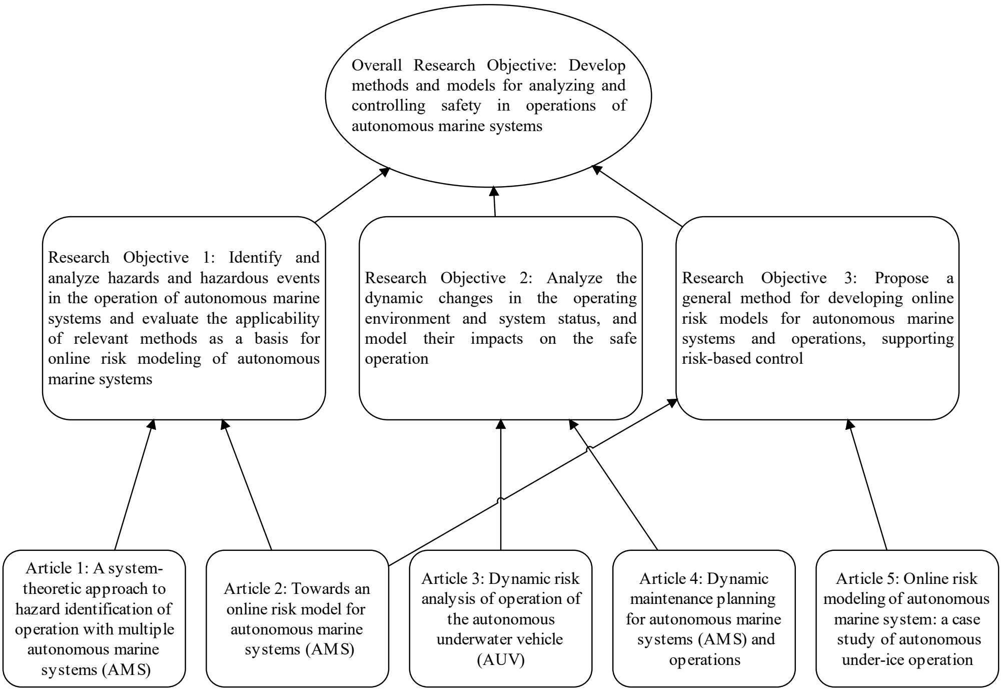

Fig. 4.15 Relationship between the overall research objective, research objectives and the research articles included in this thesis.

4.2.1 Contribution to Research Objective 1

The contribution to RO 1 identifies and analyzes potential hazards/ hazardous events in AMS operations and investigates the knowledge gaps of applying existing hazard identification and risk analysis methods for online risk modeling of AMS. RO 1 is achieved by Articles 1 and 2.

Article 1 explores the safety-related issue on the operation with multiple participating AMS, focusing on the unsafe interactions between the participating system/ subsystems. Taking an integrated USV-AUVs operation as an example, the analysis contributes to this research objective by exploring the applicability of using a systematic approach, i.e., STPA, in the hazard identification analysis in the case of operations with multiple AMS.

More importantly, the results in Article 1 demonstrate that loss scenarios can be caused by various unsafe interactions, e.g., between AMS and environment, between AMS and other AMS, and between AMS and human operators. These unsafe interactions have the potential to further lead to several system losses that are unacceptable to stakeholders. These results contribute to this research objective by highlighting the importance of considering the unsafe interactions in a hazard identification or risk assessment in AMS operations.

Taking an AUV under-ice operation as a case study, the first contribution of Article 2 to RO 1 is a comprehensive hazard identification works with a number of potential hazards/ hazardous events that may affect the safe operation of AMS. The identified hazards/ hazardous events contribute to RO 1 by indicating that various aspects can be influential to the safe operation of AMS, including maintenance and reliability aspects, software failure, human-machine interaction, operating environment, traffic and operational hazards, human error, and operational procedure.

In addition, Article 2 identifies a list of evaluation criteria for online risk models for AMS through a system engineering process. This provides a holistic understanding of the aspects that should be considered and included when developing an online risk model for AMS. In terms of RO 1, this contributes a practical tool to assess the efficiency of existing methods as a basis for developing online risk models.

Based on the identified evaluation criteria and the hazard identification results, the more important contribution of Article 2 to RO 1 is the evaluation results on the applicability of existing hazard identification and risk analysis methods for online risk modeling of AMS. It was found through Article 2 that STPA can be considered a good basis for developing an online risk model, considering the number of criteria fulfilled and its ability to handle the interaction among systems and software failure. PHA and procedural HAZOP may not be satisfactory methods compared to STPA. However, they can be used as complementary tools to STPA to address its difficulties in determining the RIFs that should be included and monitored from an exhaustive list of unranked loss scenarios and identifying specific RIFs that are related to human operators in the operation of AMS. The conclusion contributes to a general understanding of the strengths and weaknesses of different hazard identification and risk analysis methods as a basis for online risk modeling.

Generally, Articles 1 and 2 contribute to RO 1 through a comprehensive knowledge on the influence of hazards/ hazardous events on the safe operation of AMS. This provides AMS designers and operators with implications for improved engineering design, operational procedures and further research. More importantly, the identified hazards/ hazardous events, their causes and consequences, and the assessment of how they are connected lay a foundation for contributions to RO 2 and RO 3. By evaluating the applicability of existing hazard identification and risk analysis methods for online risk modeling of AMS in Article 2, the contributions of RO 1 provide an appropriate first step towards a general framework for online risk modeling for AMS.

In summary, the project results in the following specific contributions in terms of RO 1:

- A case study of an integrated USV-AUVs operation that demonstrates the application of STPA in the hazard identification analysis in the case of operations with multiple AMS.
- Highlighting the importance of considering the unsafe interactions in a hazard identification or risk assessment in AMS operations.
- Comprehensive hazard identification works with a number of potential hazards/ hazardous events that may affect the safe operation of an under-ice AUV operation through PHA, procedural HAZOP, and STPA.
- A list of evaluation criteria for online risk models of AMS, which can be used a practical tool to assess the efficiency of existing methods as a basis for online risk models.
- Comprehensive evaluation of the applicability of relevant hazard identification and risk analysis methods for online risk modeling of AMS.
- STPA can be considered a good basis for developing an online risk model, while PHA and procedural HAZOP can be used as complementary tools.

4.2.2 Contribution to Research Objective 2

RO 2 is to analyze the dynamic changes in the operating environment and system status, and model their impacts on the safe operation. This objective is addressed through Articles 3 and 4.

In general, Article 3 contributes to RO 2 by proposing a general method to quantitatively assess the risk of AUV operation subject to the effect of dynamic changes in the operating environment based on DBN models.

For building the risk model, six types of potential operating environments of most AUVs operations, and the potential critical environmental factors for each type of operating environment, are determined in the article. For quantitatively determining the dynamic changes in an operating environment and assessing the environmental impacts on the system, an approach based on a DBN model and online location information is proposed in Article 3. This work provides a practical tool for determining the operating environment during a mission and calculating the corresponding probability values of various consequences

As far as the system status of the AMS is concerned, component degradation and potential operational management, such as maintenance operations, contribute to a large extent to its change during operation. In fact, component degradation and maintenance operations are closely linked and together affect the system status and thus the safe operation of AMS. Therefore, it is critical to understand the state of each component in the AMS, analyze their impact on the system status, and develop a dynamic and appropriate maintenance plan for the entire system, accordingly. However, no previous work has been done in the area of AMS maintenance planning. In general, Article 4 contributes to RO4 by proposing a dynamic maintenance planning method for AMS based on the dynamic change of component/ system status, dependencies among components, and the constraints of potential maintenance opportunities to improve the safe and economical operation of AMS.

Firstly, Article 4 contributes to RO 2 by pointing out the challenges in maintenance planning in the case of AMS operations, including high consequence of AMS shutdown, limited and irregular maintenance opportunities, and various dependencies among components i.e., economic dependence, structural dependence, or stochastic dependence.

In terms of the high consequences of AMS shutdown, e.g., blackout of an autonomous ship, Article 4 contributes to RO 2 by analyzing the mechanism by which components lead to the system shutdown. To achieve this, both critical components and non-critical components are considered. The structural dependence and stochastic dependence in various types of components are captured using the Markov model. Furthermore, Article 4 applies a multiphase Markov model to deal with the potential changes in the maintenance strategies and system status, addressing the challenge posed by the limited and irregular maintenance opportunities in the context of AMS. Maintenance grouping is applied in Article 4 to deal with economical dependencies among components. A heuristic approach is proposed to address the challenge of combining all the above techniques.

In addition, the analysis and discussion on grouping horizon emphasize the necessity to avoid "short sightedness" in the context of AMS maintenance planning, which provides both theoretical and practical implications. To demonstrate the application of the proposed method, the maintenance planning of an autonomous ship is performed as a case study.

The developed models in Articles 3 and 4 provide a good understanding of the dynamic operating conditions during the operation of AMS. These highlight the necessity to enhance the intelligence of the AMS, its situation awareness, and decision-making for managing and reducing risks; therefore, the necessity to address RO 3.

In summary, the PhD project results in the following specific contributions in terms of RO 2:

- Identification of the potential operating environments of AUVs and the potential critical environmental risk factors.
- Proposal for a dynamic risk analysis method based on a DBN model for determining the dynamic changes in the operating environment and assess their impact on the system.
- Proposal for a dynamic maintenance planning method for AMS based on the changes in component/ system status, dependencies among components, and the constraints of potential maintenance opportunities.
- Identification of the challenges in maintenance planning in the case of AMS operations and solving them by combining multi-Markov model and grouping algorithm.

- Longer grouping horizon is suggested in the context of AMS maintenance planning.
- A case study of autonomous ship to demonstrate the proposed method for dynamic maintenance planning.

4.2.3 Contribution to Research Objective 3

The third research objective (RO 3) is to propose a general method for developing online risk models for autonomous marine systems and operations, supporting risk-based control. Article 5 is the main contribution to RO 3, while Article 2 contributes to it by providing parts of the theoretical basis, as mentioned in Section 4.2.1.

First, Article 5 contributes to RO 3 with a complete framework for the online risk modeling, in which STPA is applied for hazard identification and BBN is applied as the risk model. In addition, Article 5 contributes to RO 3 by solving specific research challenges in developing the online risk model. For example, challenges of converting the developed BBN model into an online risk model, such as evidence uncertainty, is explored and addressed. With real-time data from sensor systems involved, specifying hard evidence based on observation is not acceptable in an online risk model due to the accuracy loss. Fuzzy discretization is thus suggested to address the challenge of evidence uncertainty.

The developed online risk model can provide a real-time estimate of the risk level during the actual operations, which is expected to support the decision-making of AMS during operations and control its safety. Article 5 further contributes to RO 3 by proposing a two-level strategy method to develop the SRC system for AMS. This enables risk-based control of the AMS, thus improving its intelligence. The case study of AUV under-ice operations demonstrates the application and practicality of the proposed online risk model and SRC system.

In general, Article 2 contributes to RO 3 by laying a foundation through providing an appropriate first step for online risk modeling and a holistic understanding of the aspects that should be considered in online risk models for AMS. Article 5 contributes to RO 3 with a complete framework for developing the online risk models and SRC system for AMS.

In summary, the project results in the following specific contributions in terms of RO 3:

- A list of evaluation criteria for online risk model for AMS, which reflect the aspects that should be considered and included in its development.
- STPA can be considered as a good basis for developing an online risk model.
- A complete framework for the online risk modeling combining STPA and BBN.
- Highlighting the importance of considering evidence uncertainty in online risk modeling and suggesting fuzzy discretization for addressing the challenges.

- Proposal for a two-level strategy to develop an SRC system for AMS operations, improving its intelligence by enabling its risk-based control.
- A case study of AUV under-ice operations that demonstrates the application and practicality of the proposed online risk model and SRC system.

4.3 Synthesis

4.3.1 Scientific implication of the research

This thesis and the associated articles contribute to the safe operation of AMS. Findings and developed models present new knowledge and insights, which are valuable for future studies in this area.

First, during the research related to RO 1, the identified evaluation criteria of online risk models point out the aspects that should be included in such models, providing a comprehensive understanding of the development of online risk modeling for future research. Considering that few studies has been conducted in terms of online risk modeling, these findings would be valuable for future works in this area. In this thesis, the hazard identification and the following risk analysis and control mainly focus on safety in terms of random hazardous events. The security issue, i.e., events related to deliberate actions, are not explicitly addressed in the thesis. Therefore, the obtained conclusion cannot be directly used for analyzing and controlling security. Further study and possible adaptation on the model are required in the future. For example, STPA-Sec, an adapted STPA method for security, might be applied.

The research contributing to RO 2 has resulted in two models that address the dynamic operating conditions. A DBN model is developed, in which a novel method to dynamically determine the critical environmental factors' effect is proposed based on stochastic modeling and real-time location information. In terms of the dynamic system status, a novel method of dynamic maintenance planning combining multi-phase Markov model and grouping algorithm is proposed to address operational and modeling challenges in the context of AMS maintenance, including high consequence of AMS shutdown, limited and irregular maintenance opportunities, and various dependencies among components. These novel methods and models may have direct scientific implications as they address the difficulties in simulating the dynamic operating conditions in AMS operations and capturing their impact.

In the research contributing to RO 3, a complete framework for online risk modeling and SRC is proposed for AMS. In this framework, the evidence uncertainty in online risk modeling and SRC system is explored for the first time. The results highlight its importance, and fuzzy discretization is suggested for this reason. This has implications for future research in the field of online risk modeling and implementation of higher autonomy in systems. In addition, a two-level SRC system is proposed, which is a structured way to improve the intelligence of AMS by making risk-based control. The developed method for online risk modeling and SRC system would be a valuable contribution to the so-called “intelligent risk analysis”, which is considered a game-changer in future research on AMS (Chen et al. 2021).

4.3.2 Practical implication of the research

Several aspects from the research have practical implication for the operation of AMS and the industry that develop or use it. As part of the Nansen Legacy project, these implications provide constructive suggestions to improve the safety and efficiency of the operation of AMS, e.g., ocean monitoring using AUV and USV.

For example, the results in Article 1 highlight the importance of considering the unsafe interactions in a hazard identification or risk assessment in AMS operations, especially in the operation with multiple AMS. In Article 2, a comprehensive hazard identification results can help designers and operators improve the safety and robustness of AMS operations in the Arctic in the future. In terms of the system design, more reliable and robust physical components and software are necessary. Adequate testing and verification of both hardware and software are suggested. In terms of the operational procedures, adequate preparation for environmental and operational challenges are highlighted for AMS operations in the harsh environment. For the AMS operations in the Nansen Legacy project, AUV operators can directly use these conclusions to improve the operational procedures and prepare for the potential adverse consequences of a failure.

It should be noted that in the Nansen Legacy project, events related to deliberate actions are not explicitly addressed since the security issue is not the main focus. However, this aspect can be essential in the AMS applications in the future, e.g., maritime transportation using MASS. Therefore, security assessment requires further study in the area of AMS operations. Considering the common part between safety/risk assessment and security assessment, the results obtained in this thesis is a good foundation.

The developed dynamic maintenance planning model highlights the importance of having a longer grouping horizon in the context of AMS operation. A method with “short-sightedness” might provide an unacceptable maintenance plan and increase the maintenance costs. The potential increasing maintenance costs have been shown in Article 4, which would be a valuable implication for the owner and operators of AMS.

Also, the change of the operating environments in AMS operation and its impact have been explored in Article 3. The results show the importance to consider various operating environments that an AMS may encounter during operation as it may cause large change in the risk value. For the Nansen Legacy project, where most research operations are conducted in harsh environments, this work highlights the need for extra attention and preparation when the operating environment may change over time.

The online risk model developed in Article 5 reveals the potential change in the risk value during the operation of AMS. It highlights the necessary to monitor safety-related factors during the operation and make risk-based control actions, accordingly. Implications of this finding will aid future development processes by incorporating risk values into AMS operation.

It is believed that the designers, owners, and operators can be beneficial from the findings in the thesis by incorporating them both in the risk assessments and practical operations, which will contribute to the safe design and safe operations of AMS.

5 Conclusion and Future Work

5.1 Concluding statements

Currently, both academia and industry are exploring the applications of AMS. Compared to conventional marine systems, however, new types of failures might be introduced into AMS operations due to unforeseen interdependencies in the system design, dynamic operating environments, maintenance challenges, insufficient situation awareness and decision-making from human operators, etc. Development of tools and methods to analyze and control the safety in AMS operations, however, are lagging. Some challenges and knowledge gaps in analyzing and controlling the safety of AMS operations need to be addressed.

Through a series of hazard identification works on AUV operations, including AUV under-ice operations and USV-AUVs collaborative operations, this thesis reveals that unsafe interactions between systems impact operation. The analysis of the potential causes and consequences lays the foundation for developing risk models for AMS operations. Considering that the future risk models for AMS should be able to assess the potential risk dynamically and support its decision-making, the applicability of using the existing hazard identification and risk analysis methods for online risk modeling were analyzed. This thesis demonstrates that STPA can be considered a good basis for developing an online risk model, while PHA and procedural HAZOP can be used as complementary tools.

A DBN-based risk model has been proposed, in which the potential environments of AUVs operations and critical environmental factors have been identified, and their impacts on the system have been evaluated. A dynamic maintenance planning method for AMS has been proposed based on the dynamic change of component/ system status, dependencies among components, and the constraints of potential maintenance opportunities. These models provided valuable insight to the safe and economic operations of AMS.

This thesis demonstrates the necessity for online risk models for AMS to enhance the safety and intelligence of the AMS, its situation awareness, and decision-making. In this thesis, a complete framework for the online risk modeling for AMS is proposed by combining STPA and BBN. Evidence uncertainty in developing the online risk model has been highlighted and addressed. Based on the developed online risk model, a practical method is proposed to develop the SRC system. The online risk model and SRC system enables the AMS to be informed of the operational risk level and make risk-based decisions, accordingly, thereby improving its intelligence.

In conclusion, the research in this thesis has highlighted the knowledge gaps and challenges and provided methods and models to address them. The case studies described in the articles demonstrate the application and feasibility of these methods and models. Even though the proposed methods and models are not tested on all different types of AMS; the operations and their characteristics have similarities. Hence, it is expected that the analysis results and conclusion in this thesis could be adapted to other AMS or autonomous systems, as well.

5.2 Future work

While carrying out the research in this thesis, several interesting research questions and ideas have arisen. It is believed that the future work research can be further carried out as a continuation of the topics of this thesis to add on values and widen the boundaries. Some of the potential research directions are described as follows.

STPA is claimed as a good basis for developing online risk models for AMS in Article 2. However, it is found that it has difficulties in determining the RIFs that should be included in an online risk model and for identifying specific RIFs that are related to human operators in the AMS operation. Although other methods, such as PHA and procedural HAZOP, might be used as complementary tools, performing the same analysis using three different methods is complicated and time consuming. A complete and structured hazard identification method for online risk models for AMS is necessary. Future studies should endeavor on this topic. For example, an adapted version of STPA that that combines the advantages of various methods might be a promising area.

Article 4 proposes a dynamic maintenance planning method. The proposed method can provide a maintenance plan for AMS based on the age of components. This is a well-known policy for determining when to perform maintenance activities. However, some failure modes are not age-related. Also, most of them give some kind of warning when they are occurring or about to occur. The maintenance plan can then be determined based on the actual condition of the components instead of age. Future research work may focus on adapting the proposed method to make use of the real-time data to develop condition-based maintenance planning for AMS. This may help to improve the cost-saving of the maintenance operations.

Development of online risk models and the SRC system for AMS is an essential contribution of this thesis. While the main framework has been proposed, some detailed aspects need further research. For example, online risk models rely on real-time sensor data and condition monitoring. Monitoring all variables might be costly, and a method to determine which variables should be prioritized for monitoring can improve the efficiency of the online risk models. In addition, to improve the accuracy of the online risk model, it would be interesting to further study how the variables can be accurately monitored and reflect the conditions of the system or environment. Incorporation with other techniques, such as machine learning, might be a promising research direction.

The development of the SRC system deserves further research. The SRC system in Article 5 takes into account the current risk level for decision-making. Another option is to utilize the online risk model, instead of estimating the current risk level, to predict the future risk level based on the current situation and the potential changes in the operating environment and system status. In this case, the simulation of the operation may work in parallel with the actual operation. The information obtained from actual operation is used to predict possible future situations, and the effects of possible future control strategies and situations are evaluated through simulation. Then, the developed online risk model can capture both the current and future risk levels. Control strategies can then be determined based on current conditions as well as future forecasts. This may further improve the intelligence of the AMS by providing more timely risk-based decisions.

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Part II - Research Articles

Article 1

Yang, R., Bremnes, J. E. and Utne, I. B. (2022). A system-theoretic approach to hazard identification of operation with multiple autonomous marine systems (AMS). *Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)*, Ireland.

A system-theoretic approach to hazard identification of operation with multiple autonomous marine systems (AMS)

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Operations with multiple autonomous marine systems (AMS) are becoming increasingly popular for a variety of applications. Some traditional challenges associated with single AMS operations may be relieved by the presence of a second AMS. However, the operation of multiple AMS may bring new challenges, possibly caused by the unsafe interaction between the participating AMS. Hence, this needs to be further analyzed to improve their safe and reliable operations. However, most previous risk-related works on AMS focuses on the operation of a single AMS and ignores the unsafe interaction between different participating AMS.

The current study focuses on the operation with multiple AMS, aiming at identifying the potential hazards during the operation. System theoretic process analysis (STPA) is applied to capture the interaction between each AMS and the interaction between AMS and human operators. An integrated USV-AUVs operation is used as a case study in this study. The analysis results are expected to support future planning of operations with multiple AMS and increase awareness of the operators. In addition, it is expected that the analysis results and conclusions can also be used to develop an online risk model which can capture the rapid change of operating conditions of operations with multiple AMS and then enhance the intelligence of the AMS, its situation awareness, and decision- making during operation.

Keywords: Maritime System Safety, Autonomous Marine Systems (AMS), Multi-vehicle Operation, Autonomous Underwater Vehicle (AUV), Unmanned Surface Vehicle (USV), STPA, Online Risk Model.

1 Introduction

The development of Autonomous Marine Systems (AMS), including Maritime Autonomous Surface Ships (MASS), Unmanned Underwater Vehicles (UUV), is expected to improve ocean monitoring, cargo and personnel transportation, and subsea production and intervention (Thieme and Utne 2017; Utne, Sørensen, and Schjølberg 2017; Komianos 2018). In particular, operations with multiple AMS are becoming increasingly popular in ocean science, but there is a potential for such use for a variety of applications.

With multiple autonomous systems working collaboratively, some previous challenges with a single system might be solved. Multiple AUVs can provide significant benefits to a variety of underwater applications, including ocean sampling, mapping, surveillance, and communication (Fiorelli et al. 2006). Taking the operation of autonomous underwater vehicles (AUV), for example, some traditional challenges associated with AUV operations, such as the limited survey area, may be reduced by the presence of a second vehicle. An unmanned surface vehicle (USV) may provide navigational updates and communication for AUVs in an integrated USV-AUVs operation.

Several studies have been conducted on operations with multiple AMS. A coupled USV-unmanned aerial vehicles (UAVs) system was proposed (Shao et al. 2019), in which UAV can effectively provide perception of wider range of surrounding dynamic environments, while the USV is a platform of the launching and landing of UAV. Sinisterra et al. (2017) developed a USV platform for surface autonomy, in which the USV serves as a mother ship for small UAV and AUV. Norgren et al. (2015) conducted an experiment with integrated USV-AUV operation, where the

USV was used to relay acoustic information sent by an AUV to an onshore operation center for remote monitoring. In addition to acting as data relay, USVs can also be used to extend the range of AUV as a launch and recovery system for AUV. Sarda and Dhanak (2016) proposed a USV-based automated launch and recovery system for AUV. The proposed concept for launch involves lowering the AUV into the water from the center of the USV while it is in motion. Recovery and retrieval involve aligning the two vehicles together through acoustic positioning and retrieving the target AUV by lowering a thin line with an outrigger-type depressor wing from a winch on the USV. Experiments with multiple different AUVs were carried out in the Mar Menor Coastal Lagoon under the collaboration of several research institutes (González et al. 2012). Salinity data is collected in two-day experiment to measure and assess the influence of the water from the Mar Menor on the adjacent area.

Due to the rapid change of operating conditions, AMS operations are considered challenging (Yang et al. 2020). Hence, operation of multiple AMS brings new challenges, such as the unsafe interaction between the systems, which should be considered in the risk analysis. However, previous risk-related works on AMS focus on the operation of a single AMS, especially on the reliability of physical components and sub-systems. The operation with multiple AMS and the possible unsafe interaction between AMS are not sufficiently considered in existing risk analysis studies. Therefore, the safety and risk aspects of the operation with multiple AMS need to be further analyzed.

The current study focuses on the operation with multiple AMS, aiming to identify the potential hazards during operation. To capture the possible unsafe interactions between each AMS, as well as between AMS and human operators, the system theoretic process analysis (STPA), is applied. An integrated USV-AUVs operation is used as a case study in the current study. The underwater acoustic navigation and communication between USV and AUV are the focus areas of the current study, which presents possible loss scenarios which may cause the system failure.

It is expected that the analysis results can support the future planning of operations with multiple AMS and increase the awareness of operators. Furthermore, the results may provide useful input to the design of AMS. In addition, it is expected that the analysis results can be used as a basis for developing an online risk model which can capture the rapid changes of the operating conditions with multiple AMS and contribute to enhancing the intelligence of the AMS, its situation awareness, and decision- making.

2 System-theoretic Approach to Hazard Identification

STPA is a hazard analysis method based on the idea of System-Theoretic Accident Model and Processes (STAMP) (Leveson 2011), in which the unsafe interactions between components are considered important contributors to an accident. Other types of hazard identification methods, Hazard and Operability Study (HAZOP) and Failure Mode and Effects Analysis (FMEA), focus on component or event failures.

Several previous studies have applied STPA to analyze the safety and risk aspects of AMS operation (Wróbel, Montewka, and Kujala 2018a, 2017, 2018b; Chaal et al. 2020; Yang et al. 2020; Yang and Utne 2022). STPA is selected in the current study for hazard identification due to the focus on system interactions, which is feasible for multi vehicle operation. The steps of STPA are presented below. More information, including its advantages, disadvantages, and limitations, can be found in previous studies (Leveson 2011; Yang and Utne 2022). They are not further discussed here due to limited article length.

Step 1: Define purpose of the analysis

The purpose of the analysis should be well defined in the first step, including determining the system to be analyzed and the system boundary. This process starts from the system level, identifying losses and system-level hazards. In terms of losses, anything valuable to stakeholders should be included. System-level hazards are defined as the system's state to possibly lead to a loss under the worst-case environment (Leveson 2011).

Step 2: Control structure development

Next, the control structure of the studied system should be developed in this step. In the STPA analysis, the system is represented as a hierarchical control structure, including feedback control loops, which enables a systematic way of identifying possible loss scenarios, which can capture the effect of unsafe interaction among components.

Step 3: Identify unsafe control actions (UCA)

Unsafe control action (UCA) is defined as the action that, in a particular context and worst-case environment, has the probability to lead to a hazard (Leveson 2011). In general, a control action can be unsafe in the following four situations: 1. Fail to provide necessary control action to cause hazards; 2. Provide control action in incorrect situations; 3. Provide a safe control in the inappropriate time or order; 4. Duration of the control action is inappropriate. In this step, UCAs are identified by considering in which situations a control action can be unsafe.

Step 4: Identify loss scenarios

Once UCAs have been identified, the next step is to identify loss scenarios, which describes the causal factors that can lead to the UCA.

According to the STPA handbook (Leveson and Thomas 2018), two types of loss scenarios need to be considered in this step; 1) the scenario that leads to UCAs and 2) scenarios in which control actions are improperly executed or not executed. The first type of scenario can occur due to unsafe controller behaviour or inadequate feedback and information, while the second type of scenario is associated with the control path or the controlled process itself.

3 Case Study

3.1 System description

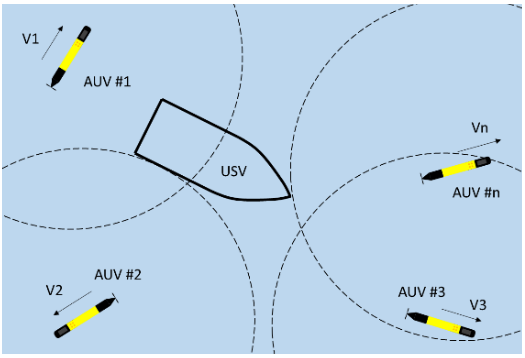

Fig. 1 Illustration of studied integrated USV-AUVs system.

Fig .1 demonstrates a schematic diagram of the USV-AUVs system with *n* participating AUVs.

It is assumed that the integrated USV-AUVs system operates in coastal areas, with the purpose of ocean monitoring. Multiple AUVs are involved and operate under water during the mission. Each AUV may operate in the mode with a pre-defined mission plan for exploring a determined area with pre-defined route waypoints or operate adaptively with higher level of autonomy to autonomously determine the exploration area and route waypoints.

An AUV uses its Inertial measurement unit (IMU) and Doppler Velocity Log (DVL) data for short-term navigation accuracy, while the long-term navigation accuracy relies on underwater acoustic navigation and communication provided by USV when global navigation satellite systems (GNSS) measurements are unavailable.

In the case study, one USV is planned to operate on the water surface to provide navigation support and communication to the AUVs while they are operating under water. Due to limited underwater acoustic range, some AUVs may not always operate within the acoustic range of the USV during the mission. Operating under water without navigational support for a long time can result in unacceptable positioning of AUVs. Therefore, the USV is expected to localize the AUVs and move dynamically on the water surface to avoid any AUVs operating for long periods of time without navigational support, thus improving the navigation accuracy of each AUV.

3.2 STPA analysis of the studied system

Step 1: Define purposes of the analysis

Based on the integrated USV-AUVs operating characteristics and previous testing experience of AUV operations, three undesired events are identified as potential losses of an integrated USV-AUVs operation, as shown in Table 1. Several additional losses in AMS operation, such as the injury to operators and negative environmental impacts, are not included in this study, but should be considered in future analyses.

Table 1 Losses associated with the operation of AUV.

Identifier	Losses
L-1	Loss of or damage to AUVs or USV
L-2	Failure of mission (loss of data, failure to inspect pipeline, etc.)
L-3	Loss of or damage to third-party assets

For an AMS operation, it is essential to guarantee that AMS can be successfully recovered after the mission. *Loss of or physical damage to AUVs or USV* will result in mission failure and a substantial increase in operating cost, which is an unacceptable loss for stakeholders. *Failure of mission* is defined as the AMS' inability to complete its mission, or the mission is aborted automatically due to safety issues. Due to local weather and logistical issues, operating time may be very limited. Once the mission fails, it may be difficult to repeat the operation multiple times. This means that the loss of mission may lead to wasted logistic cost, including infrastructure management, transportation, and launch and recovery systems. Other third-party assets, such as engineering structures like subsea pipelines and offshore platforms, may also be close to the operating environment. When an AMS cannot maintain a safe distance from the aforementioned objects, *loss of or damage to third-party assets* may occur. They are also unacceptable to stakeholders and should also be considered in the hazard analysis of AMS operations.

Table 2 System-level hazards and related losses.

Identifier	System-level hazard	Related losses
H-1	USV/ AUV's integrity is lost	L-1; L-2
H-2	USV/ AUV does not maintain safe distance from terrain and other objects	L-1; L-3
H-3	AUV fails to follow emergency plan when needed	L-1; L-2;
H-4	USV fails to provide sufficient navigation support to AUV	L-1; L-2; L-3
H-5	Operators lose the control/ communication to USV	L-1; L-2; L-3
H-6	AUV does not complete the mission (AUV does not follow the designated mission path/ gather data)	L-2;
H-7	USV/ AUV is not retrieved or salvaged after missions or mission abortion	L-2

Given the identified losses, system-level hazards can then be determined. A total of seven system-level hazards have been identified in this study, as shown in Table 2. These system-level hazards are considered to have the potential to result in corresponding losses in the worst-case operating conditions. Each system-level hazard may trigger more than one loss, as shown in Table 2.

Step 2: Control structure development

A system is defined as "a set of interrelated elements that are organized to carry out a specific function or a set of functions in a specific environment" (Rausand 2013). All components associated with the system should be considered to develop the hierarchical control structure. Generally, an AMS operation may involve human operators, navigation system, supporting system, etc. In this study, human operators, USV and multiple AUVs are selected as main elements in the system.

Before the operation, the human operators define the mission and send the defined mission plans to AUVs and USV respectively. An emergency/ safety plan is usually defined and sent along with the mission plans. The emergency plan is usually a predefined plan to avoid a completely system failure during operation, e.g., sending the vehicle to a designated location once any fault or failure is detected. Human operators may also provide basic manual controls such as speed up/ down and steering.

Given the AUV mission plan(s), either predefined mission or adaptive mission, the guidance module (in AUV) will continuously provide route waypoints to the control module based on the current estimated state for AUV. Then, the control algorithms in the AUV will provide appropriate forces of thruster, rudder and fins in order to complete the mission. The estimated states for an AUV rely on several types of information and sensor data for navigation and position estimation, including the information of propeller and fin/rudder information, IMU data, DVL data and compass data. The above information, however, can only accurately provide short-term states estimation while an AUV is operating under water, the long-term accuracy of state estimation of under-water AUV during the mission relies on the acoustic navigation and communication with USV.

The basic control structure of USV is similar to that of the AUVs. Since the USV aims to provide navigation support for the AUVs, however, the route waypoints of USV depend on both the USV and AUVS' states so that it can follow specific routes to get close to some AUVs if necessary. In addition, since the USV is operating on the water surface, a relatively accurate position can be obtained using GNSS data.

Fig. 2 presents the hierarchical control structure model of the integrated USV-AUVs operation, highlighting a specific AUV (AUV#1).

Interactions between other AUVs and USV are simplified in this study due to their similarities with AUV#1 and the article length. This structure demonstrates the main interactions between the identified component. Available control actions from the controllers are represented by the red arrows, while feedback signals provided by actuators are represented by the blue arrows. The abstract of the control structure is extracted based on the characteristic of typical AUVs and a typical USV.

Step 3: Identify unsafe control actions (UCA)

Given the hierarchical control structure developed in Fig. 2, the UCAs related to the USV-AUVs operation can be determined by considering all the control action. For each control action, four categories of UCAs, as mentioned in Section 2, are considered to identify the actions that have the potential to cause hazards. Considering that the difficulties of AUV navigation and the communication between USV and AUV in the current case study, the control action *Position of AUV#1 (Ultra-short baseline (USBL) update); Transfer data /communication; Stop the mission; Start another mission; Start emergency plan* is taken as an example to demonstrate the UCAs identified for integrated USV-AUVs operation. The related system-level hazards for each UCA are presented in the followed bracket. In the current control action, no UCAs that caused by applying a control action for too early / late or too long / short were identified.

Step 4: Identify loss scenarios

This subsection analyzes how the identified UCAs may occur by determining loss scenarios and derives the possible reasons to prevent the corresponding UCA.

Taking UCA18-N-1 (Navigation system module in USV does not provide AUV#1 position (USBL update) to AUV#1 in time when the AUV#1 is operating under water) for example, four possible loss scenarios are identified as presented in Table 4. The development of the loss scenario considers unsafe controller behaviour, scenarios involving the control path, etc.

In order to eliminate or mitigate the occurrence of the identified causal scenario, further analysis should be performed to identify the possible reasons. S-1 and S-2 of UCA18-N-1 are related to reliability characteristics of the physical components in acoustic module in USV or AUVs. The corresponding reliability levels should be guaranteed at the design stage and tested before operations.

Table 3 Unsafe control actions identified for the integrated USV-AUVs operation.

CAs	Not provided	Provided	Provided too early / late	Provided too long / short
Position of AUV#1 (USBL update); Transfer data /communication; Stop the mission; Start another mission; Start emergency plan; [From Navigation system module (in USV) to Navigation system module (in AUV#1)]	(UCA18-N-1) Navigation system module in USV does not provide AUV#1 position (USBL update) to AUV#1 when AUV#1 is operating under water [H-2] [H-4] [H-6] (UCA18-N-2) Navigation system module in USV does not provide command of stopping the mission, or starting another mission when the current mission is finished [H-1] [H-2] [H-4] [H-6] (UCA18-N-3) Navigation system module in USV does not provide command of starting emergency plan when operators believe there is issue and send the command of starting emergency plan [H-1] [H-3]	(UCA18-P-1) Navigation system module provides unacceptably inaccurate AUV#1 position to AUV#1 when the AUV#1 is operating under water [H-2] [H-6] [H-7]	N/A	N/A

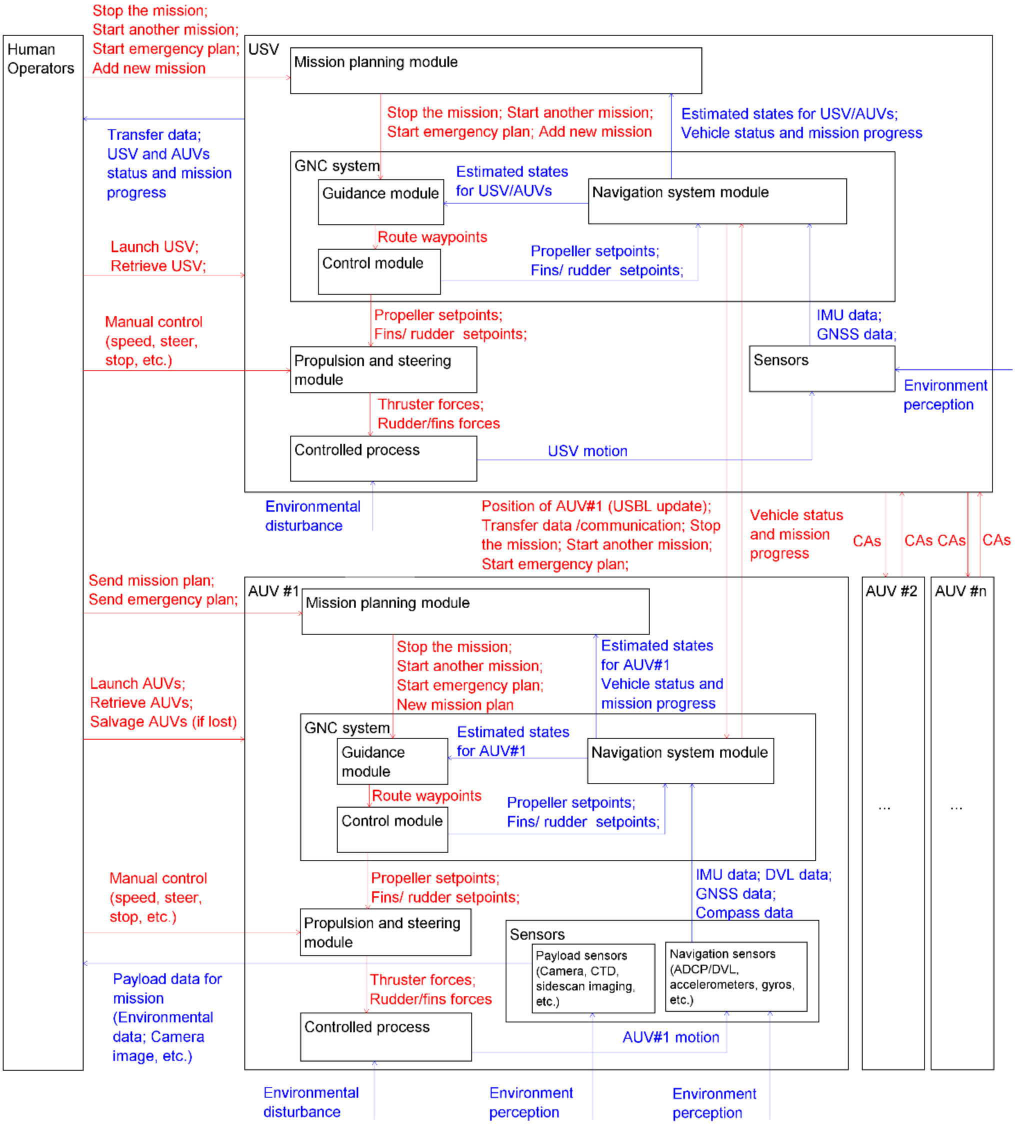

Fig. 2 Hierarchical control structure diagram for integrated USV-AUVs operation.

S-3 and S-4 of UCA18-N-1 are scenarios related to the failure of acoustic navigation or communication. They are developed considering two possible failure mechanisms of acoustic navigation and communication: (1) the reduced received signal strength due to large distance between AUV and USV, and (2) the deteriorated received signal due to ambient noise and multipath propagation. These scenarios consider the control path of the corresponding control action. A more detailed analysis of these scenarios and appropriate management of them during the operation can improve the AUV's situation awareness and the decision-making during the operation. Therefore, considering the possible improvement of safety level during operations, S-3 and S-4 of UCA18-N-1 are further analyzed to identify the causal factors through a brainstorming process by gathering experts in this area and asking what factors can cause the occurrence of these scenarios.

Table 4 Loss scenarios for UCA18-N-1.

Identifier	Loss scenarios
S-1	Failure of the acoustic module in AUV#1, leading to the failure of the range measurement between USV and AUV#1.

Table 4 (continued)

S-2	Failure of the acoustic module in USV, leading to the failure of the range measurement between USV and AUV#1.
S-3	AUV#1 is outside of the acoustic range of USV for a too long time, leading to the failure of the range measurement (due to acoustic signal attenuation)
S-4	Deterioration of the acoustic signal due to noise, leading to the failure of the range measurement between USV and AUV#1.

The acoustic signals are attenuated with distance travelled. Thus, once an AUV is outside of the acoustic range of USV for too long a time (S-3 of UCA18-N-1), the failure of a range measurement may occur. The causal factors of S-3 may include:

(i) Incorrect waypoints provided by the guidance module (software failure), making the USV move to an inappropriate direction (e.g., towards another AUV for navigation support when unnecessary), leading to AUV#1 being of the acoustic range of USV for a long time.

(ii) The multi-AUV mission is not appropriately planned by the human operator, so that the path planning algorithm of the USV is not able to provide navigational support to every AUV in time, leading to AUV#1 being out of acoustic range of the USV for a long time.

(iii) Bad weather conditions (strong wind, currents, and waves) making the USV move away from AUV#1, leading to AUV#1 being out of the acoustic range of USV for a long time.

(iv) USV is stuck in a place, e.g., grounding, making it hard to get close to AUV#1 due to the previous following of another AUV.

(v) AUV#1 does not operate as planned, which cause an unexpected long distance between USV and AUV#1.

(vi) USV followed another AUV in the previous movement, which causes an unacceptably long distance between USV and AUV#1 afterwards.

(vii) AUV#1 is outside of acoustic range of the USV (due to acceptable reasons, e.g., the mission of AUV#1 makes it move far from USV or USV moves towards another AUV for navigation support). However, the USV fails to move and get close to AUV#1 to provide navigation support in time due to:

- Incorrect or poor propeller/fins/rudder setpoints due to failure in code or software
- Physical failure of propeller/fins/rudders
- Reduced propulsion performance due to low power level
- USV is hard to move and does not get close to AUV#1 in time due to restrictions of unexpected terrain or obstacle, e.g., existence of third-party structure (fish farm, buoy, etc.).

Even if the acoustic signal is received, the quality of the received signal may affect the interpretation of the signal, and thus affect the range measurement (S-4 of UCA18-N-1). The causal factors of S-4 may include:

(i) High ambient noise (includes ship traffic, biological noise, weather, geological activity, etc) causing a deteriorated received signal

(ii) Multipath propagation (e.g. due to reflections from ocean stratification or bathymetry), leading to a deteriorated received signal

(iii) Doppler effect, leading to a deteriorated received signal

(iv) Frequency response, leading to a deteriorated received signal

4 Conclusion

New challenges with multiple AMS operations, such as the unsafe interaction between the systems, are not well considered and addressed in previous studies. To solve this problem, the current study focuses on the safety and risk aspects of the operation with multiple AMS, aiming to identify the potential hazards caused by unsafe interactions between participating systems. A systematic hazard identification method, namely STPA, is applied in this study.

An integrated USV-AUVs operation is used as a case study. A hierarchical control structure diagram for the integrated USV-AUVs operation is developed. The STPA focuses on the underwater acoustic navigation and communication between the USV and multiple

AUVs, the current study presents the potential UCAs and corresponding loss scenarios that may lead to the system losses. Two loss scenarios related to the failure of acoustic navigation or communication are further analysed with respect to identifying causal factors: (1) the reduced signal strength due to increased distance between AUV and USV, and (2) the deteriorated received signal due to high received noise. The analysis results of loss scenarios and their causal factors demonstrate that unsafe interaction between AMS can be crucial to the safe operation of multiple AMS, so they should be fully considered and resolved before and during the operation.

The analysis results provide input to improved design of AMS and are expected to support future operations planning with multiple AMS and increase operators' awareness. In addition, the analysis results and conclusions can be used as a basis for developing online risk models to capture the rapid change of operating conditions and to enhance the situation awareness, and decision-making of the AMS.

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Towards an online risk model for autonomous marine systems (AMS)

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ABSTRACT

Considering that few or no human operators are directly involved in the operation of Autonomous Marine Systems (AMS), an online risk model is necessary to enhance the intelligence of the AMS, its situation awareness, and decision-making. The current study identifies the criteria for an online risk model for AMS, which can be used to assess its validity and effectiveness.

Taking an under-ice Autonomous Underwater Vehicle (AUV) operation as an example, the current work investigates how different risk analysis methods, namely the Preliminary Hazard Analysis (PHA), the Systems Theoretic Process Analysis (STPA), and Procedural Hazard and Operability Analysis (HAZOP), contribute to fulfilling the different criteria for online risk modeling of AMS. The analysis results show that STPA can be considered a good basis for developing an online risk model due to its relatively good coverage of the identified evaluation criteria, especially its ability to handle the interaction between system and software failure. In addition, considering some shortcomings of using STPA and the changing role of human operators in the AMS operation, PHA and Procedural HAZOP can be used as complementary tools. It is expected that the analysis results and conclusions can be adapted to other AMS as well.

1. Introduction

The development of Autonomous Marine Systems (AMS), including Marine Autonomous Surface Ships (MASS), Unmanned Underwater Vehicles (UUV), and autonomous offshore oil and gas systems is emerging due to the potential for improved safety and efficiency. Compared to conventional marine systems, AMS are expected to operate with few or even no crew onboard in the future, and it is therefore essential to ensure that AMS have the expected level of reliability, availability, maintainability and safety to be acceptable for widespread use at sea. At the very least, AMS should be as safe as conventional marine systems (Laurinen, 2016). Hence, risk assessment is a necessary tool for the safe operation of AMS and to provide information for decision-makers, including both operators and the AMS itself.

Several previous studies have been conducted focusing on risk aspects of AMS. Chaal et al. (2020) proposed a framework for the Systems Theoretic Process Analysis (STPA) and its hierarchical control structure of an autonomous ship by making use of the knowledge gained in traditional ship operation, assuming that automated controllers will replace human controllers. Wróbel et al. (2017, 2018a, b) established a possible safety control structure for autonomous ships and conducted safety analysis to provide design recommendations for autonomous ships in terms of regulations, organization, and technology. Thieme et al. (2018) assessed the applicability of several existing ship risk models to MASS. The results demonstrate that, with extra consideration of the aspects of software and control algorithms and human-machine interaction, some existing risk models might be used as a basis for developing relevant risk models for MASS. Thieme and Utne (2017) proposed a process for developing safety indicators for the operation of AMS, reflecting the safety aspects of AMS operation to assist in operational planning, daily operational decision-making, and identification of improvements.

Several risk-related studies have been conducted specifically for UUV. Utne and Schjølberg (2014) proposed a taxonomy for hazardous events. Further, the results demonstrated that the main risk to humans in Autonomous Underwater Vehicle (AUV) operations in Arctic areas is during the launch and recovery of the vehicle. In a study by Brito and Griffiths (2011), a Markov chain model was applied to assess the reliability of AUVs, capturing the different states of the AUV operation. Step sequences from prelaunch to operation to recovery were included in this study, and a total of 11 discrete states were identified. A case study using the fault history of the Autosub3 AUV was conducted to provide the information for different operational phases. In another study by Brito and Griffiths (2016), the Bayesian approach was used to predict the risk of AUV loss during their missions. This research provided a rigorous

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Abbreviation

ADCP	Acoustic Doppler Current Profiler
AMS	Autonomous Marine Systems
BBN	Bayesian Belief Network
BT	Bow Tie
CMBRA	Condition Monitoring-Based Risk Assessment
CTD	Conductivity, Temperature, Depth
DBN	Dynamic Bayesian Network
DRA	Dynamic Risk Assessment
DVL	Doppler Velocity Logs
ETA	Event Tree Analysis
FPSO	Floating Production Storage Offloading
FTA	Fault Tree Analysis
GNSS	Global Navigation Satellite System
HAZOP	Procedural Hazard and Operability Analysis
HCL	Hybrid Causal Logic
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LBL	Long Baseline
LoA	Levels of Autonomy
MASS	Marine Autonomous Surface Ships
OH&S	Occupational Health and Safety
PHA	Preliminary Hazard Analysis
RIFs	Risk Influencing Factors
ROV	Remotely Operated Vehicles
STAMP	System-Theoretic Accident Model and Processes
STN	Single Transponder Navigation
STPA	Systems Theoretic Process Analysis
SVA	Security Vulnerability Analysis
UCAs	Unsafe Control Actions
UUV	Unmanned Underwater Vehicles
VHF	Very High Frequency
VTS	Vessel Traffic Service

procedure for AUV risk management in hazardous environments.

Loh et al. (2019) conducted a risk assessment for AUV under-ice missions to explore the risk of AUV missions in a harsh environment. Historical fault log data, as well as expert knowledge, were used in this study to develop a risk model. More studies on the risk analysis of AUV operations can be found in the review article by Chen et al. (2021). Hegde et al. (2018a, 2019) developed dynamic safety envelopes for autonomous Remotely Operated Vehicles (ROV). In these studies, the Octree method was used to set up the cuboidal shape of the proposed safety envelope, while the size of the dynamic safety envelope was determined by modeling a fuzzy inference system.

With few or no operators, an AMS needs improved perception, situation awareness, and planning/re-planning capabilities compared to the conventional marine system. For safe operation of the AMS, risk should be an essential factor that needs to be monitored and taken into account for control action. Therefore, an online risk model that is able to assess the possible risk dynamically and support the decision-making of the AMS is necessary (Utne et al., 2020). Few works, however, have been conducted to identify the specific needs for an online risk model of AMS and to analyze the applicability of the existing methods.

The current study identifies criteria for online risk models for AMS, using the systems engineering process. The identified evaluation criteria reflect the aspects that should be considered and included when developing an online risk model for AMS. In the paper, an AUV is used to investigate how the different existing risk analysis methods, i.e., Preliminary Hazard Analysis (PHA), STPA, and Procedural Hazard and Operability Analysis (HAZOP), contribute to fulfilling the criteria for online risk modeling of AMS. Further, the results from the analyses are evaluated with respect to developing an online risk model. Since the criteria are more or less generic, it is expected that the analysis results and conclusion could be adapted to other AMS as well.

The paper is structured as follows: Section 2 demonstrates the need for online risk modeling of AMS. The criteria for the assessment of the online risk models for AMS are identified in Section 3. In Section 4, some existing methods that might be used as a basis for the online risk models are briefly introduced. Risk analyses of an AUV under-ice operation using PHA, STPA, and Procedural HAZOP are performed as a case study in Sections 5 and 6. Section 7 summarizes the results from three methods for improved engineering design, operational procedures and further research, and investigates how the different analyses contribute to fulfilling the criteria for an online risk model of AMS. Section 8 concludes the current study and analyzes how the results from the analyses can be used to develop an online risk model.

2. On the need for online risk modeling of AMS

A risk model is a qualitative or quantitative representation of a system, measuring its risk level. In order to accurately measure the risk level, risk models are developed to capture the interaction between subsystems or events based on risk analysis. A typical risk analysis tries to answer three main questions (Rausand, 2013): (1) What can go wrong? (2) What is the likelihood of that happening? and (3) What are the consequences? Different types of risk analysis have been developed in the past decades and with different advantages and disadvantages, and they have been applied in a wide range of fields in both research and industry.

Traditional risk methods and models, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), usually provide a static risk picture of a system or an operation based on historical data or expert knowledge, but cannot capture the change of the system's risk level, which may deteriorate with time due to natural and management causes. In order to deal with the possible time-varying risk level, the concept of Dynamic Risk Assessment (DRA) was proposed, which aims 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" (Khan et al., 2016).

Several studies have been conducted to address the dynamic risk model in the past decade to take advantage of updated information, especially using Bayes' theorem (Baksh et al., 2018; Barua et al., 2016; Khakzad et al., 2012, 2013; Liu et al., 2021; Paltrinieri et al., 2014; Wang et al., 2017; Yang et al., 2020a). Khakzad et al. (2012) proposed an updated Bow Tie (BT) method to achieve dynamic risk assessment by updating safety barriers of BT using Bayes' theorem. The prior failure rate of each safety barrier is assumed to follow a gamma distribution. The number of failures over time is taken into account to form likelihood functions, which is then used to update the failure rate estimation using Bayes' theorem. A novel Bayesian Belief Network (BBN) framework was developed by Baksh et al. (2018) to model marine transportation accidents in Arctic waters. The model is capable of updating the results whenever new evidence is available during the operation using Bayes' theorem.

Barua et al. (2016) developed a dynamic operational risk assessment method for the chemical process industries, which takes into account the sequential dependency and the effect of time. The changes of variables over time are represented as the temporal dependencies between two discrete time slices using conditional probability in a Dynamic Bayesian Network (DBN). Several studies used a similar approach in other fields, such as fire accidents (Wang et al., 2017) and AUV operations (Yang et al., 2020a).

Most of the existing DRA methods, however, rely on incident/accident statistics or temporal dependence based on historical or experience data to update the risk estimation, which means that they must wait until accidents or near misses occur before updating the estimation of the risk indexes (Zio, 2018). Therefore, these methods may fail to reflect the rapid changes of the operating environment and system status and provide timely support for decision-making during the operation of AMS. The development of wireless technology, cheaper and more advanced sensor technology, and improved computational capability are promoting the development of a more dynamic and online risk assessment (Vinnem et al., 2015; Zio, 2018).

The concept of online risk management was first proposed by Vinnem et al. (2015), in which the online risk models are built on data from different sources, including historical data, sensors and measurements, and experience data. With the help of appropriate data interpretation methods, online risk models provide pre-warnings of possible operational deviations. Though the framework was first proposed for Floating Production Storage Offloading (FPSO), the concept has in recent years been used in other fields, such as for autonomous ships (Utne et al., 2020). A similar idea to the online risk model was also proposed by Zio (2018), which is called Condition Monitoring-Based Risk Assessment (CMBRA). While most existing DRA methods rely on statistical data for risk estimation to update risk, the proposed CMBRA enables the risk estimation to be updated by using condition-monitoring data.

Utne et al. (2020) outlined a framework for online risk modeling for an autonomous ship. The hazard identification is conducted using the STPA, and the results are used to develop a BBN risk model, in which sensor data can be used to measure monitorable variables as part of the autonomous ship's supervisory risk control. Zeng and Zio's (2018) work presents a dynamic risk assessment method, combining statistical and condition-monitoring data, that allows for the estimation of risk based on data collection during operation. A BBN model with simulations is developed to utilize two types of data: statistical data provides the historical information about the system, while condition-monitoring data provides the degradation status of the specific target system and describes system-specific features. Several other studies also attempt to make use of condition-monitoring data in risk assessment (Kim et al., 2015; Lazakis et al., 2016; Zadakbar et al., 2015).

3. Evaluation criteria for the online risk model of AMS

To identify relevant criteria for the online risk model of AMS, a system engineering process is used, based on (Blanchard, 2004). The functional requirements for AMS with respect to risk and online risk models are described. The requirements identified are then used to derive the evaluation criteria, which reflect aspects that should be represented in an online risk model for AMS. The purpose is to identify potential gaps and focus areas that need to be especially addressed when developing online risk models for AMS. Furthermore, the purpose is to assess the efficiency of existing risk methods as a basis for such models.

3.1. Functional requirements

Table 1 summarizes the functional requirements of AMS with respect to risk. This table is adapted from the work of Thieme et al. (2018), expanding the scope from MASS only to online risk modeling of other AMS, such as UUVs, and autonomous offshore platforms. During the operation, the AMS should identify in a timely way the potential hazards and hazardous events (R1.1), supporting the decision-making and risk control by either operators or the system itself. Hardware, such as machinery, sensors, and the control system, need to perform their desired function during the operation (R1.2). Compared to conventional marine systems, the software and algorithms involved in AMS will increase. Issues due to the introduction or increase of the software in AMS should be solved. The software and algorithms should execute their functions in a reliable and safe manner and be verified before and during operation. Since new faults are usually introduced to the code during updates, a reliable and verified software update should also be guaranteed (R1.3). In addition, the interaction between software and hardware should be robust enough to guarantee safe operation (R1.4).

Table 1
Requirements for AMS with respect to risk, adapted from Thieme et al. (2018).

Requirements	Description
R1.1	Reliable and timely identification of hazards and hazardous events
R1.2	Reliable and verified hardware during operation (sensors, machinery, and control system)
R1.3	Reliable and verified software and algorithms and software updates during operation
R1.4	Robust interaction between software and hardware
R1.5	Reliable and adequate communication/interaction between AMS (includes crew if any) and the external supporting system (if any)
R1.6	Reliable and adequate communication between AMS and other marine stakeholders
R1.7	Reliable and adequate provisions for adaptive autonomy/mode
R1.8	Accessible and affordable human–machine interfaces

Some external supporting systems might be involved during the operation of AMS, e.g., a UUV requires an underwater navigation system, and MASS and UUV may require a control basis/center for remote supervision and control. Therefore, if any external supporting system is involved, the communication and interaction between them and the AMS should be adequate and reliable (R1.5). The interaction and communication with other marine stakeholders and environments, such as other ships, marine structures, and the Vessel Traffic Service (VTS), should also be considered during operation (R1.6).

Autonomous ships may switch between various operational modes with different Levels of Autonomy (LoA) due to the rapidly changing environment or complex nature of tasks (Thieme et al., 2018; Yang et al., 2020b). Other AMS, such as ROV, may also need to operate in an adaptive autonomy/mode (Hegde et al., 2018b; Yang et al., 2020b). Reliable and adequate provisions for adaptive autonomy/mode are required in the AMS operation (R1.7). Human-machine interactions and cooperation are expressed by various LoAs, and each level specifies a different degree of operation between fully manual operation and highly autonomous operation (Vagia et al., 2016). Although the ultimate goal is to have highly autonomous systems, human operators are still required for each AMS, currently and in the near future. Thus, it is necessary to have an accessible and affordable human–machine interface (R1.8).

Table 2 summarizes the requirements for a general online risk model. The risk spectrum of the system or operation is expected to be measured by utilizing various sources of data, including historical data, expert knowledge, and especially the monitoring data from sensors (R2.1). With the help of online data, online risk models are expected to provide a real-time risk picture and pre-warnings of possible operational deviations (R2.2). By capturing data and information during the operation

Table 2
Requirements for a general online risk model.

Requirements	Description
R2.1	Utilize various sources of data, especially the monitoring data from sensors, in order to provide the risk spectrum of the system or operation
R2.2	Dynamic in order to capture the quick changes in operation
R2.3	Update models with new information, data, and scenario for better risk evaluation and emerging risk
R2.4	Capture the possible changes of involved subsystems or components and their impacts on risks during the operation
R2.5	Efficiently identify RIFs that need to be monitored online or in real time during operation
R2.6	Effectively model the correlation among identified RIFs to estimate the overall risk level
R2.7	Capture the uncertainty in the model, especially the uncertainty caused by sensors and the data fusion algorithm

using the monitoring technique, an online risk model should be able to update the model, in terms of both the model itself and the type of input data, for better risk evaluation and emerging risks (R2.3).

The system or operation may involve different subsystems or components in different phases in a task. The relevant data that needs to be considered and monitored in the risk model may change over time. In addition, due to changes in the interaction between the subsystems, new hazards may evolve, and the acceptable risk level of the operation may also change accordingly. An online risk model should be able to reflect these changes in different phases during an operation (R2.4). A risk model needs to identify factors that may affect the level of risk. These factors are called Risk Influencing Factors (RIFs), which are defined as "a set of conditions which influence the level of specified risks related to a given activity or system" (Rosness, 1998). By monitoring the states of the RIFs, early warnings about possible deviations from the normal operating envelope of a system can be provided (Utne et al., 2020). In order to efficiently monitor the system and provide an accurate risk evaluation, an online risk model should efficiently identify RIFs that need to be monitored online or in real time during operation (R2.5). The last two requirements are similar to those of traditional risk models and the existing dynamic risk models. The online risk models should be able to effectively model the correlation among identified RIFs and reflect the overall risk level of the system (R2.6). The uncertainty should be properly handled in online risk models, especially the uncertainty caused by sensors and the data fusion algorithm that is caused by the increase in the use of monitoring techniques (R2.7).

3.2. Evaluation criteria for online risk modeling of AMS

The evaluation criteria for online risk models of AMS are derived based on the requirements identified in Tables 1 and 2. The criteria are developed considering that the online risk model should be used for the AMS itself to operate autonomously, and/or for the human operators to monitor the operational situation. Table 3 summarizes the criteria identified for the online risk model of AMS. The evaluation criteria reflect the aspects that online risk models of AMS need to cover. The current list of evaluation criteria can be used to assess the validity and effectiveness of online risk models. It is also expected to be used as a guide to check whether any important aspects of the online risk model are missing and what new information should be included.

Table 3

Evaluation criteria for online risk modeling of AMS.

Identifier	Criteria for online risk modeling of AMS	Addressed requirements
C1	Inclusion of maintenance and reliability aspects of system performance	R1.1, R1.2
C2	Inclusion of the performance of software and control algorithm	R1.1, R1.3
C3	Inclusion of the performance of the interaction between software and hardware	R1.1, R1.4
C4	Inclusion of the performance of the interaction between AMS and external supporting system	R1.1, R1.5
C5	Inclusion of the performance of the communication between AMS and environment	R1.1, R1.6
C6	Inclusion of the hazards and possible changes in risk models caused by adaptive autonomy/mode or the change of involved subsystems	R1.1, R1.7, R2.4
C7	Inclusion of human–machine interaction	R1.1, R1.8
C8	Inclusion of security issues	R1.1-R1.8
C9	Inclusion of various sources of data to estimate the risk level, especially sensor data	R1.1, R2.1
C10	Level of knowledge (in both the studied system and risk) needed for analysis	R2.1
C11	Be able to update risk level with new information/ data	R2.2
C12	Be able to deal with emerging risk (the way that the model is changed and/or updated with new data)	R2.3
C13	Be able to efficiently identify RIFs that need to be monitored online or in real time during operation	R2.5
C14	Be able to effectively model the correlation among identified RIFs	R2.6
C15	Be able to deal with the uncertainty, especially the uncertainty from the sensor and real-time data or the data fusion algorithm	R2.7

4. Development of online risk models

The first step of risk analysis is to identify what can go wrong, and relevant methods include Hazard Identification (HAZID) and the STPA. The PHA is an extended version of HAZID that also addresses the likelihood and consequences, usually in a semi-quantitative manner. Procedural HAZOP is used to review procedures and operational sequences. Hence, the STPA, PHA and Procedural HAZOP may therefore provide a desirable foundation for developing an online risk model.

Some previous studies have been conducted on the comparison of different methods, such as STPA and HAZOP (Sultana et al., 2019) or STPA and FMEA (Rokseth et al., 2017), against various aspects to demonstrate how one method can be used to replace another, or how one method can be used as complementary to another one. The current study, however, aims at analyzing the applicability of different methods to the online risk modeling of AMS, identifying advantages and disadvantages over the identified criteria and determining appropriate methods based on the analysis result. Information from each method that can be utilized to further develop an online risk model is also identified.

The PHA is usually used to identify hazards and potential accidents in the early stages of system design and has been successfully applied to safety analysis in many fields, such as process plants and offshore marine systems (Rausand, 2013; Vinnem and Røed, 2019). The term "preliminary" reflects that the analysis results are usually refined through additional and more thorough studies when more information on the system becomes available. Hence, a PHA is typically used to provide an initial risk picture for the system, but may also be used as a stand-alone analysis. Still, when a more comprehensive risk assessment is necessary, the analysis results can also be used to screen events for further research, making it possible for them to become the basis of online risk models.

A HAZOP study is a structured and systematic hazard identification process that examines how a system may deviate from the design intent and results in hazards and operability problems that may represent risks to personnel or equipment. The studied system is divided into several simpler sections called "study nodes" that are analyzed one by one later (Rausand, 2013), by using a set of guidewords and process parameters. The analysis is carried out by a group of experts from different research areas (a HAZOP team) in a series of brainstorming sessions. The HAZOP approach was initially developed to be used during the design phase, but can also be applied to systems in operation. Several variants of the original HAZOP approach have been developed (Rausand, 2013). Procedural HAZOP is considered a powerful tool for risk assessment of new or changed operations and is applicable for all activities where an operational procedure is used (Vinnem and Røed, 2019).

STPA is a hazard analysis method mainly based on the idea of System-Theoretic Accident Model and Processes (STAMP), in which safety is controlled by enforcing constraints on the system behavior (Leveson, 2011). Unsafe interaction among the components in a system is believed to be the main reason leading to an accident, instead of considering that the accident is the result of a chain of component or event failures. The hazardous events occur due to the absence, presence, or the improper timing of control actions. The method is usually selected due to its ability to model complex interactions. In general, the process of STPA consists of the following steps:

- Step 1: Define the purpose of the analysis, including system to be analyzed and also the analysis boundary. Hazardous events at system level and safety constraints need to be identified as well.

- Step 2: Develop the hierarchical control structure of the system to be analyzed. Interactions among the components are represented by control actions and feedbacks.
- Step 3: Identify Unsafe Control Actions (UCA) that violate the safety constraints.
- Step 4: Develop loss scenarios in which UCA may occur and identify their causes.

The methods mentioned above cannot be used for developing online risk models directly, but based on such methods, more detailed risk modeling can be performed, using, for example, BBN, FTA, ETA, Hybrid Causal Logic (HCL), simulation-based approaches, etc. The current study aims to analyze the applicability of PHA, STPA and Procedural HAZOP as the starting point for online risk modeling of AMS, but the development of a comprehensive model is outside the scope of the current work.

5. Case study

5.1. Under-ice operation of AUV

An AUV under-ice operation is used as a case study to investigate how PHA, Procedural HAZOP, and STPA contribute to fulfilling the criteria for an online risk model of AMS.

As a part of the Nansen Legacy project (The Nansen Legacy), AUVs are used to collect environmental data of the oceans, and under the ice in the Arctic region in the near future. Arctic operations, however, involve risks related to loss of the vehicle and mission abortion, due to the harsh environmental conditions for vehicles and human operators and difficulties in AUV navigation. Loss of the vehicle and abrupted or aborted missions are costly due to the high expenses related to the vessels used for the field cruises, but the consequences are also related to the failure to collect the data used for ocean monitoring and science. Furthermore, loss of the vehicle has a negative environmental impact in terms of adding to the “garbage” in the oceans. Compared to the traditional AUV operation, the difficulties with under-ice operations include but are not limited to the following:

- Logistical challenges due to remote areas and limited infrastructure
- Harsh environmental conditions for operation, such as the low temperature and the presence of ice
- Navigation challenges of the Arctic area
    - o The large vertical component of the magnetic field reduces the accuracy of the magnetic compass
    - o The low horizontal component of the Earth’s rotation reduces the accuracy of the gyroscopic compass

To improve the safety and robustness of under-ice operations with AUVs in the Arctic, an online risk model is needed to provide decision support for the human operators and the AUV itself. In this research, the NTNU REMUS 100 AUV has been selected to perform under-ice operations, considering its robustness and previous under-ice track record. Details about this AUV can be found in (Norgren et al., 2020). Considering that most AUVs have similar characteristics to the NTNU REMUS 100 AUV, the results obtained from this work should also be valid for most AUVs.

5.2. System description

Fig. 1 demonstrates the schematic diagram of the preliminary design of the AUV operation using under-ice navigation buoys, currently under development at NTNU. The design aims to deploy navigation buoys along the planned AUV transect, providing AUV navigational support during the mission. The concept of Single Transponder Navigation (STN) is applied, making use of the short-term positioning accuracy provided by the high-performance dead-reckoning navigation system in the AUV and bounded long-term accuracy provided by the buoys system (Norgren et al., 2020). When the AUV is operating under ice, it will measure the distance to the buoys via acoustics. In addition, since the buoys may drift with ice and ocean currents, the buoys need to obtain the position through the Global Navigation Satellite System (GNSS) and transmit it to the AUV via acoustics. Combined with the position estimation from the high-performance dead-reckoning navigation system in the AUV, relatively good navigation performance can be obtained. Equipped with several environmental sensors, the AUV is expected to collect data. More detailed information on the system can be found in the study by Norgren et al. (2020). With the help of the designed system, the AUV operation in the current case study aims to search for the temperature gradient and follow the route that decreases with the temperature gradient. PHA, Procedural HAZOP, and STPA have been applied to analyze the possible risks of the operation.

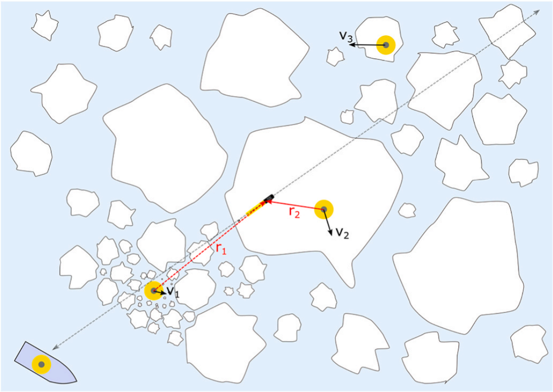

Fig. 1. AUV operation using the under-ice navigation buoys, designed by Norgren et al. (2020).

6. Main results and findings of the case study

The current section presents the main results and findings from the three methods.[1] The analyses involve risk analysts and AUV experts with experiences from several previous Arctic AUV operations with vehicles from NTNU, especially from a research cruise to the North Barents Sea in November 2019. The AUV operations provide the participants in the analyses with field experience on environmental conditions and the challenges of AUV operation in the Arctic, including underwater navigation challenges, technical and operational failures, and logistical challenges.

6.1. Main findings from PHA

The PHA was conducted through three PHA workshops, which gathered people from different fields of expertise, i.e., risk assessment and AUV operation. The workshops resulted in several hazardous events, which were identified and analyzed with respect to their assumed frequencies and expected consequences. In the analysis, Table 4 and Table 5 were used for the categories of frequency and consequence, respectively. The expected consequences were identified considering the principle of the credible worst-case before any risk reduction measures have been implemented. Fig. 2 presents the risk matrix used in the current risk analysis, where the risk index is a semi-quantitative measurement of risk and defined as “the logarithm of the risk associated with the event and is found by adding the frequency class

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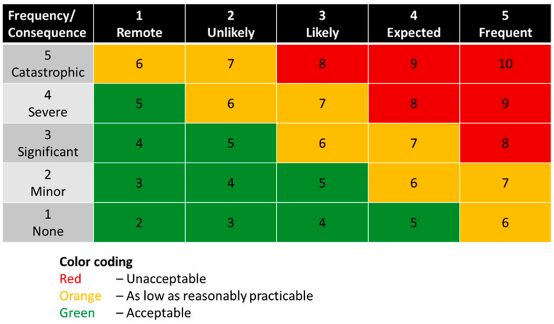
[1] More detailed results of the analyses can be provided by contacting the corresponding author (Ruochen Yang. ruochen.yang@ntnu.no)

Table 4
Frequency categories for use in the current PHA.

Index	Category	Frequency (per operation)	Description
5	Frequent	>1	The event is likely to occur more than once per operation.
4	Expected	Around 1	The event may occur once per operation
3	Likely	1–0.1	The event may occur once per operation/ten operations
2	Unlikely	0.01–0.1	The event will be most likely not to occur
1	Remote	<0.01	The event is unlikely to occur

Table 5
Consequence categories for use in the current PHA.

Index	Category	Consequence	Description
5	Catastrophic	Loss of AUV/injuries to the operators	Loss of time (over 100 days), over 1,000,000 NOK
4	Severe	Major damage to the system (AUV/buoys)/loss of several buoys	Loss of time (100 days), 500,000 NOK-1,000,000 NOK
3	Significant	Mission failure (unable to repeat)/no data/loss of one buoy	Loss of time (ten days)/data, 500,000 NOK
2	Minor	Minor influence of mission/unacceptable data/Minor damage to the system	Loss of time (one day)/data
1	None	No damage/influence	No loss of time/data



Frequency/ Consequence	1 Remote	2 Unlikely	3 Likely	4 Expected	5 Frequent
5 Catastrophic	6	7	8	9	10
4 Severe	5	6	7	8	9
3 Significant	4	5	6	7	8
2 Minor	3	4	5	6	7
1 None	2	3	4	5	6

Color coding
Red – Unacceptable
Orange – As low as reasonably practicable
Green – Acceptable

Fig. 2. Risk matrix for use in the current PHA.

of the event with the severity class of the event" (Rausand, 2013). Different colors represent the level of acceptance.

The PHA focused on the hazardous events related to the REMUS AUV system's technical hazards, technical hazards of the navigation buoys system, environment, traffic and operational hazards, and human error. Table 6 summarizes the most hazardous events and their possible causes, consequences, and suggested risk reduction measures. It is found that the technical hazards of the REMUS AUV and the harsh environment contribute most to the risks of the AUV's under-ice operation.

In terms of the technical hazards of the REMUS AUV, the AUV's navigation and communication system module failure and software failures are considered to be the most hazardous events, which may directly lead to a loss of the AUV. Risk-reducing measures are proposed to mitigate these risks. Considering the rapidly change of operating environment, unexpected navigation challenges in the Arctic, and relatively little experience with under-ice operation, the navigation and communication system module and other components should be fully tested under different operating conditions before operation. In order to avoid unwanted software failure, software verification and testing, especially for own-developed software (control algorithm and software configuration), should be carried out before operation.

Unacceptable hazardous events associated with the environment include the low maneuverability caused by the strong current and the potential accidents caused by Arctic sea ice, such as the collision with ice or stuck under ice. In order to mitigate the risk, enough preparations are needed to retrieve and salvage the AUV, such as the acoustic pinger for pinpointing AUV's location and tools for cutting ice. These also require human operators to be well trained and familiar with the retrieve and salvage process in the Arctic.

6.2. Main findings from procedural HAZOP

The entire AUV operation is divided into five main phases in the current study, including pre-deployment, deployment, operation, recovery, and post-deployment. It was summarized by the designer of the system, who has over seven years of work experience in AUV operation. Procedural HAZOP was applied to identify deviations from the way the system is intended to function: their causes, and all the hazards and operability problems associated with these deviations. Each main step in the operational procedure is regarded as a "study node" in the current HAZOP work. A list of guidewords used for identifying deviation was agreed on by all experts before analysis, as shown in Table 7.

The current Procedural HAZOP analysis was conducted through three HAZOP workshops, gathering same analysts as the PHA workshops. Table 8 shows examples of the analysis results. Though most hazardous events related to human operators and operational procedure are identified in the phases of pre-deployment, deployment, and recovery due to the operators' high involvement, these hazardous events may affect other phases or even the whole operation phases as well, and lead to an unacceptable consequence. For example, the failure of testing of communication between buoys may result in a non-functional buoy and then cause navigation failure during the operation phase and lead to the loss of AUV. The results in Procedural HAZOP highlight the importance of the proper testing and verification of software and hardware in AUV and buoys and adequate preparation for environmental and operational challenges before the operation phase.

6.3. Main findings from STPA

The STPA analysis was initially performed by the first author and then reviewed and revised by the same analysts as in PHA and Procedural HAZOP workshops. The STAMP Workbench software (Information-technology Promotion Agency, 2021) was used to develop the control structure and further analysis.

A hierarchical control structure diagram for AUV under-ice operation is shown in Fig. 3. It demonstrates the main interactions between each component in the system. Available control actions from the controllers are represented by the red arrows, while feedback signals provided by actuators are represented by the blue arrows. Generally, the operation may involve the human operators, the AUV, the navigation system, the supporting system, etc. In this study, the AUV, operators, and navigation buoys systems are selected as the main elements in the system.

Given the hierarchical control structure developed in Fig. 3, the UCAs can be determined by considering all the control actions. For each control action, four categories of UCAs are considered to identify the actions that have the potential to cause hazards (Leveson, 2011). Table 9 presents an excerpt of the UCAs found in the case study. No UCAs that were caused by applying a control action for too long or for stopping too early were identified.

The causal scenarios can be identified by analyzing how the identified UCAs may occur. The current case study takes UCA5-P-1 (Navigation system module provides (unacceptable) inaccurate estimated position and heading during the mission) as an example to show the

Table 6
Unacceptable hazardous events and risk reduction measures obtained from PHA.

Hazardous event	Cause	Consequence	Risk			Risk-reducing measures/ actions
			Fr.	Cons.	RI	
Technical hazards of REMUS AUV system						
Navigation and communication system						
Bad Long Baseline (LBL) range measurement: Multipath etc.	Multipath from ice	Poor navigation signal or loss of navigation, making AUV fail to identify its position, follow the desired path, and collect satisfactory data	5	3	8	
Software system						
Failure of software system on operator's computer	Low battery on computer	Unable to connect AUV, probably leading to loss of AUV	3	5	8	Conduct testing in different weather conditions
Failure of software system on AUV	Bad configuration of software (modified by operators)	Unable to provide desired control/ navigation, probably leading to loss of AUV	3	5	8	Software verification, especially testing own software before operation
Failure of self-designed software (inside AUV)	Bad configuration of software	Unable to provide desired control/ navigation, probably leading to loss of AUV	3	5	8	Testing of configuration before operation
Environmental hazards						
AUV is unable to reach the planned retrieval point	Strong water current causes AUV to fail to reach /remain in the planned retrieval point.	Failure/hard to retrieve AUV, leading to loss of operation time or AUV	3	5	8	Testing and practice/training of the operators. Prepare pinger for triangulation pinpoint; prepare chainsaw for fast hole. Use snowmobile. Know direction of current.
AUV gets stuck under ice	AUV battery depleted	Unable to float to surface freely, probably loss of AUV due to difficulties in pinpointing position	3	5	8	Testing and practice/training of the operators. Prepare pinger for triangulation pinpoint; prepare chainsaw for fast hole. Use snowmobile. Know direction of current.
Collision/contact with floating ice	Ice in diving/surfacing area	Damage to antenna, making it difficult to connect to operators, probably leading to loss of AUV	3	5	8	Test and verify the reliability of antenna before operation
Human error						
Insufficient test before operation	Human error	Faults are not recognized during planning phase. Emerging risk may lead to loss of AUV	4	5	9	Set up a test checklist for operators, and make sure that operators follow the testing procedure before operation

derived loss scenarios and causal factors, as presented in Table 10. Five possible scenarios are identified for UCA5-P-1, taking into account unsafe controller behavior (such as inadequate control algorithm), inadequate feedback and information, etc. Since AUV relies on navigation buoy for navigation, AUV may provide unacceptable inaccurate states estimation during the mission if the inaccurate position is provided to AUV, or the position of buoys is not updated to AUV. In addition, the failure of software, navigation system module in AUV, or the failure of measuring accurate depth, altitude and AUV speed might also lead to the unacceptable inaccurate estimated position and heading. Given the loss scenarios identified, a more detailed analysis can be performed to identify the casual factors. Related casual factors include the distance between buoy and AUV, reliability and uncertainty of acoustics of navigation buoy and AUV, reliability and uncertainty of GPS signal, etc.

7. Discussion

7.1. Main risks and implications for improved engineering design, operational procedures and further research

The results from the above analyses may assist designers and operators to improve the safety and robustness of vehicles and operations in the Arctic in the future.

Firstly, a relatively high number of potential hazardous events and/or UCAs can be traced back to the failure of the physical components in the AUV or buoys. In conventional AUV operation in open water, a fail-to-safe mechanism of floating to the surface is common when any fault is detected, such as a leakage in the AUV. Instead, due to the possible existence of ice coverage in AUV under-ice operation, a commonly used fail-to-safe mechanism is to park the vehicle on the bottom and wait until it is guided to a safe location (Ferguson, 2008). However, when any critical component fails during the operation, such as the leakage in the

Table 7
Guidewords used in current Procedural HAZOP study, based on (Broadleaf, 2018; IEC, 2016).

Guidewords	Topics for discussion in the workshop
No action	Step is missed or omitted; intended AUV operation did not occur; action impossible; AUV or supporting system (buoy or research vessel) not ready
Less action	Human operator does less than intended; hardware does not perform as required; not enough time to complete the step
Wrong action	Human operator does the wrong thing, starts the wrong job, reads the wrong instructions; personnel perform different or out of date procedure; perform two or more steps at the same time
Out of sequence	Human operator misses out a step; carries out a step before it should occur, or after it
More time	Human operator takes longer than necessary over action (leaves something running and gets distracted); starts next action later than expected
Less time	Human operator carries out action too quickly; starts next action earlier than expected
No information	No information or feedback from the process or operation; procedure does not specify expected performance; no specified actions for emergencies
Wrong information	Information provided is wrong, out of date or contradictory (oral instruction vs. written, other procedures or steps within this procedure)
Clarity	Step is confusing; words are confusing; readability; poor procedure form layout; written in non-English language; not clearly understandable
Training	Adequate training; level of certification required and provided for this step; procedure control (issuing, updating, revisions, overriding, communication, distribution, and acknowledgment, retraining)
Abnormal conditions	Emergencies; recovery from abnormal situations; utility failure; severe or unusual weather; deviation from procedure; make-shift operations
Safety	Personnel protection; Occupational Health and Safety (OH&S) law compliance; industrial hygiene issues; environmental considerations; fire, explosion or chemical release potential

AUV or the physical failure of the propeller, waiting on the bottom for a period to find the safe location might be challenging.

The predefined fail-to-safe mechanism may not be performed as intended, and this may directly lead to the loss of AUV considering the difficulties to salvage under-ice AUV. Therefore, compared to the operation in open water, more severe consequences can be incurred if there is any failure of the physical components in the AUV or buoys. From the perspective of engineering design, the operation of AUVs in the Arctic requires more reliable and robust physical components. According to the analyses results, adequate testing and verification of the components' reliability in various operating environment before operation are suggested. Also, a more effective fail-to-safe mechanism is helpful to deal with the challenge of retrieving the AUV.

Compared with hardware failure, operators may be more interested in the risk related to software or control algorithm in the operation of AMS since these contribute most uncertainty and unexpected hazardous events. A good example is the challenges of underwater navigation in the Arctic. All three methods identify navigation failure or error as a major issue. Several underwater navigation difficulties may pose challenges related to this, for example, the multiple paths from ice and seabed due to successive reflections at the interfaces when signals transmit, high ambient acoustic noise caused by either natural or man-made sources, and lost signal caused by buoys drift out of the acoustic range.

An inadequate algorithm for calculating and mitigating the navigation uncertainty can result in the loss of AUV, since it may be difficult for the AUV to determine an accurate location for retrieval. Therefore, a more robust algorithm is needed to deal with the navigational uncertainty. Testing and verification of all onboard software should be performed to ensure quality of software application and design. In terms of drifting buoys, more reliable algorithm can be applied to simulate and predict the drifting of the buoys to prevent the buoys from drifting out of the acoustic range during operation. Deploying the buoys in a relatively closer distance to possible AUV operating path can also be effective. In addition, several RIFs or risk indicators related to underwater navigation might be crucial for limiting the uncertainty in navigation, such as the distance between AUV and buoy and standard deviation of reported buoy's position, an onboard online risk model that can capture these values can be helpful to reduce the risk of operation.

Although the human operators are not directly involved and have little control of the vehicle during the operation phase of AUV mission, hazards in operational procedures will still have a great importance to the safety of AMS operation. According to the results, these can be associated with inadequate system design, defective software development, insufficient preparation and testing, improper operation steps and behaviors, limited work schedule, etc. The three analyses highlight the importance of adequate preparation for environmental and operational challenges. A packing list of necessary equipment for operation and recovery and a checklist operational procedure should be provided to human operators to avoid missing of necessary equipment and operational steps. Due to the logistic challenges of the operation in the Arctic, such as limited time of operation and recovery caused by unexpected challenges with testing and deploying AUV or buoys in the Arctic, schedule change of research vessel, etc., a good communication with crew of research vessel and cruise leader should be ensured and a possible backup plan for operation is necessary.

The above indicates a need for further research in the domain of autonomous operation in the Arctic. Engineering design and operational procedures, for example, need to be improved. Since the scope of the paper is not on the design of the AUV, the next subsections focus on the use of the analyses results for online risk modeling only.

7.2. *Applicability of using the results in online risk modeling of AMS*

This section analyzes the applicability of the three methods to the identified criteria of online risk modeling of AMS. Table 11 summarizes the main findings from the analysis results, and the following subsections present detailed arguments and observations supporting these assessments based on the analysis from the case study. The current study does not rank the importance of these criteria, since each derived criterion covers important aspects of online risk models. However, stakeholders may be more interested in criteria that reflect the main difference between conventional marine systems and AMS, or between traditional risk models and the online risk model (for example, criteria C2, C3, C4, C6, C8, C9, C11, C15) than other criteria. Analysts may focus on different criteria when developing an online risk model, depending on the type of AMS, available data, etc.

Generally, compared to the other two methods, STPA shows better applicability in terms of the number of criteria fulfilled. The STPA results demonstrate a more detailed analysis of the risk caused by the software and control algorithms due to its ability to handle the risk caused by unsafe interaction. The visualization of the interaction between the AMS and external systems is very valuable in the analysis of AMS operation, in which these interactions might bring more issues compared to the operation of traditional marine systems. Although the current study does not consider the security issue and adaptive mode, other studies show the method's capability. The main disadvantage of STPA for an online risk model is that it provides a list of hazardous events without any ranking or quantification of the risk, making it difficult for analysts to determine which RIFs should be selected for inclusion in the model.

Table 8
Examples of hazardous events and risk reduction measures from Procedural HAZOP.

Guide word	Deviation	Possible causes	Consequence	Existing control	Action required
Pre-deployment					
Less action	Operators do not/unable to test acoustic communication between all buoys and AUV (successfully)	Test repeated in the same buoy	Navigation failure during operation/ mission abortion/loss of vehicle/unable to send command/limit the navigation range	Checklist for testing before operation (make sure operator remembers and follows the checklist)	Mark each buoy with label/bring the ranger and test
Deployment					
No action	Failure to deploy slave-buoys at desired locations	Ice condition/no (not enough) required tools/	Failure to provide navigation to AUV/ no deployment of AUV operation/ mission delay/drift of the buoy out of range	Send list of required tools before mission; check the required tools on board/check availability/ check expected ice thickness information with other groups	Bring enough tools for ice on the cruise
Less action	Operators do not/unable to test communication (Very High Frequency (VHF) radio, iridium) between all buoys successfully	Hardware failure (e.g. transmitter, power for drive board)/ software failure/forget/configuration issue/may not be successful if not tested in water	Delay mission start/unable to operate/ navigation failure during operation	Checklist (make sure operator remembers)/ avoid operation if there is issue	
More time	Take longer time to deploy buoys and AUV	Ice condition; weather; polar bear; not properly prepared; not good communication with other research teams (the mission is put on the waiting list for longer time)	Mission delay, less operation/ investigation time	Be polar bear guard ourselves; pass the shooting course; good communication with other research teams	
Operation					
More time	Delayed report of the AUV status	Acoustic multipath; not good acoustic communication condition; condition of the buoy software	Normally not critical; don't understand the information and make wrong decision (battery level is reported late)	Get Conductivity, Temperature, Depth (CTD) profile to know the acoustic communication condition	
Wrong	information	Status of AUV is not correctly reported during the mission (critical error is detected when it is normal)	Software error; sensors issue	Mission abort; lose data; lose AUV	Proper test/ preparation; need to recover AUV if the reported status is not feasible
Recovery					
No action	Operators unable to recover the AUV/ buoys	Bad handling; ice condition; buoy is frozen; ship doesn't allow its recovery (bad weather, polar bear); navigation problem may cause AUV to be unable to pinpoint the place to recover (navigation error should be fine)	Longer to recover; damage to the AUV/ buoy; deplete AUV battery (and possibly lose AUV due to no communication then)	Good handling; be aware of the ice/bear condition, weather condition; bring enough equipment for recovery (rope, tripod)	

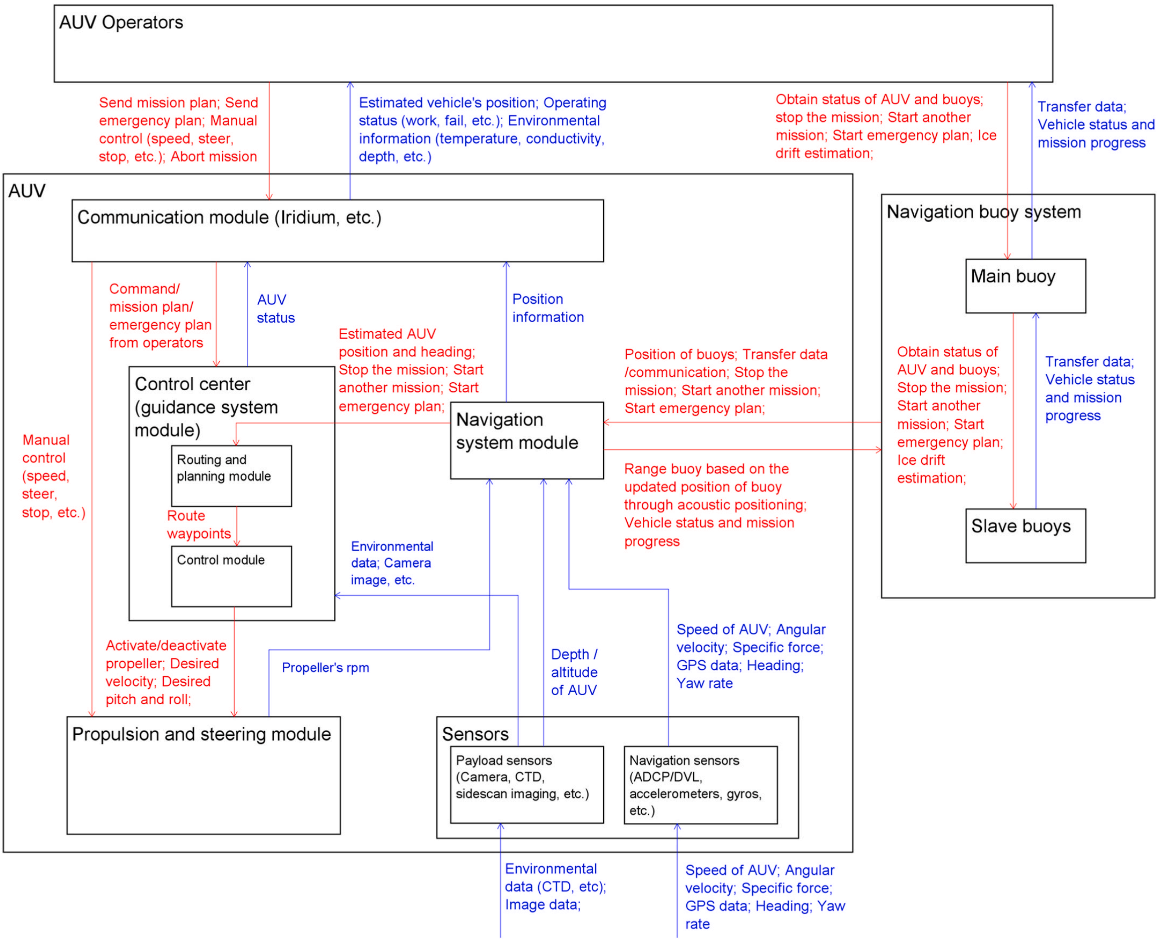


Fig. 3. Hierarchical control structure diagram for AUV under-ice operation.

The PHA results provide a good understanding of the system with the relatively low knowledge and experience level required. It performs well with respect to identifying reliability and maintenance aspects, but it may be challenging to provide a detailed analysis of software-related failures without a detailed hazard list. In terms of the environmental influence, PHA provides a clearer view than STPA by explicitly considering the impact of various environmental factors, making it a preferred method for operations in harsh environments like the Arctic or space. Semi-quantitative results enable analysts to rank the importance of identified hazardous events and make PHA easier to use as a basis for further building of online risk models. The ability to handle adaptive autonomy, software-related failures, and security issues makes it difficult to become an ideal online risk modeling method. However, considering the acceptable results obtained and less time spent on PHA, it could serve as a basis for developing STPA, where developing the control structure and UCAs is challenging for inexperienced analysts. The analysis results can help analysts better understand the system and its interaction with other systems, thereby developing a more satisfactory control structure and UCAs.

In terms of evaluation criteria, the behavior of Procedural HAZOP is unsatisfactory in aspects such as the ability to deal with the reliability-related issue, software-related issues, adaptive autonomy, and security issues. However, it does provide some results that are not covered by the other two methods. With a detailed operational procedure, Procedural HAZOP mainly focuses on the behavior of human operators. In the analysis of the environmental impact and the human-machine interaction, it provides much better results related to operators' behavior than PHA or STPA, which makes it an excellent complementary tool for them.

According to the analysis results in Table 11, none of the three methods contribute to all the online risk model criteria. More details are provided in the next subsections.

7.2.1. Inclusion of maintenance and reliability aspects of system performance

In general, both PHA and STPA show good coverage in terms of the aspects of reliability and maintenance.

In PHA, this aspect is mainly reflected in technical hazards related to both the REMUS AUV and the navigation buoys system. The system is broken down according to its physical structure during the analysis. For example, in the navigation and communication system of the REMUS AUV, various failure modes of the GNSS system, Long Baseline (LBL) transducer, Inertial Navigation System (INS), Acoustic Doppler Current Profiler (ADCP), etc., can be well listed and analyzed. Based on the experience from the current study, operators or AUV experts are familiar

Table 9

Examples of UCAs identified for the AUV under-ice operation in the Arctic.

CAs	Not providing	Providing causes hazard	Too early/Too late
Estimated AUV position and heading [from navigation system module to routing and planning module]	(UCA5-N-1) Navigation system module does not provide estimated position and heading during the mission [SC1][SC2][SC5][SC6] (UCA5-N-2) Navigation system module does not provide command to stop the mission/start another mission when the current mission is finished [SC5][SC6] (UCA5-N-3) Navigation system module does not provide command to start emergency plan when operators believe there is an issue and send the command to start emergency [SC1][SC2][SC3]	(UCA5-P-1) Navigation system module provides (unacceptable) inaccurate estimated position and heading during the mission [SC1][SC2][SC5][SC6] (UCA5-P-2) Navigation system module sends the command to stop the mission/start another mission/emergency plan when the current mission is working smoothly and successfully [SC5][SC6]	(UCA5-T-1) Navigation system module sends the command to stop the mission/start another mission too late when the current mission is already done [SC6] (UCA5-T-2) Navigation system module sends the command for emergency plan too late when the failures/mistakes are detected [SC1][SC3]
Activate/deactivate propeller; desired revolutions per minute (rpm) for each thruster; desired pitch and roll; perform emergency plan [from control module to propulsion and steering module]	(UCA6-N-1) Control module does not provide desired rpm (higher or lower) when the vehicle is close to other objects [SC1][SC2][SC6] (UCA6-N-2) Control module does not provide desired pitch/roll (higher or lower value) when the vehicle should follow the designed path [SC5][SC6] (UCA6-N-3) Control module does not provide "performing emergency plan" command when failure/pre-defined situation occurs [SC1][SC3]	(UCA6-P-1) Control module provides "Mission aborts, and emergency plan" command when the AUV is working smoothly and successfully [SC6] (UCA6-P-2) Control module activates propeller when the vehicle is already in the designed location and should stop for a while for next stage [SC5][SC6] (UCA6-P-3) Control module activates propeller when the vehicle stops and is close to other objects [SC1][SC2] (UCA6-P-4) Control module deactivates propeller when the vehicle is on the way to the designed location [SC5][SC6] (UCA6-P-5) Control module provides undesired pitch/roll (higher or lower value) when the vehicle should follow the designated path (temperature gradient) [SC5][SC6]	(UCA6-T-1) Control module deactivates propeller too late when the vehicle is close to other items [SC1][SC2]

with the physical components of the system; thus, almost all the physical components can be included with the help of design details and expert experience. With a typical checklist of possible hazards, PHA can provide a complete and detailed analysis in terms of reliability and maintenance.

The control structure used in STPA is a functional model, not a physical model like a physical block diagram, and the control actions or feedbacks do not necessarily reflect the physical interactions (Leveson and Thomas, 2018). Given that the UCAs identified are based on the control structure, the aspects of reliability and maintenance can be considered when analyzing the loss scenarios for UCAs. This process can be done by asking: 1) why would UCAs occur; and 2) why would control actions be improperly executed or not executed, leading to hazards. For example, the navigation system module provides (unacceptable) inaccurate estimated position and heading during the mission (UCA5-P-1) if the correct depth or altitude of the AUV is not provided, which can be

Table 10

Loss scenarios for UCA5-P-1: Navigation system module provides (unacceptable) inaccurate estimated position and heading during the mission [SC1][SC2][SC5][SC6].

No.	Causal scenarios	Possible reasons (causal factors)
S1	Necessary inputs are received, but the estimation algorithm fails to provide correct value of estimated position and heading (inadequate control algorithm), which results in wrong estimated position and heading	1) The specified control algorithm is flawed (software failure), e.g., parameters are not tuned sufficiently, leading to incorrect navigation calculation 2) Navigation error is not well handled in the algorithm, leading to unacceptable calculation accuracy of the position
S2	Position and heading of AUV is not correctly estimated since the position of buoys is not updated successfully (delayed)	1) Buoy is out of the acoustic range due to ice drift—ice drift is not correctly estimated by operator before operation, which causes the navigation buoys to be placed in the wrong position 2) Failure of acoustics of navigation buoy, leading to the failure of navigation 3) Failure of acoustic module in AUV, leading to the failure of navigation 4) GPS of navigation buoy fails to provide accurate position due to electromagnetic interference or atmospheric conditions
S3	Position and heading of AUV is not correctly estimated because the correct depth or altitude of the AUV is not received. As a result, the dead reckoning technique cannot provide correct navigation estimation	1) Failure of Conductivity, Temperature, Depth (CTD) sensor to collect depth data 2) Failure of Acoustic Doppler Current Profiler (ADCP)/Doppler Velocity Logs (DVL) to collect AUV speed 3) Failure of Inertial Measurement Unit (IMU)
S4	Position and heading of AUV is not correctly estimated because the correct speed of the AUV is not received. As a result, the dead reckoning technique cannot provide correct navigation estimation	1) Failure of ADCP/DVL to collect AUV speed. 2) Incorrect information/feedback of the propeller's rpm
S5	Position and heading of AUV is not correctly estimated because navigation system module fails to accurately measure the distance between the vehicle and navigation buoy	1) Failure of acoustic module in AUV, leading to the failure of navigation 2) High ambient noise, leading to the failure of navigation 3) Multipath from ice, leading to the failure of navigation

Table 11
Applicability of different methods to the online risk modeling of AMS.

Criteria	PHA	Procedural HAZOP	STPA
C1	Y	P	Y
C2	P	P	Y
C3	I.I.	I.I.	I.I.
C4	Y	P	Y
C5	Y	Y	Y
C6	I.I.	I.I.	Y
C7	P	Y	Y
C8	P	P	Y
C9	N	N	N
C10	L	L	H
C11	N	N	N
C12	P	P	P
C13	Y	Y	Y
C14	N	N	N
C15	N	N	N

Abbreviations: Y-Yes, N–No, P-Partial, I.I.-Insufficient information, L-Low, H-High.

traced back to the failure of the Conductivity, Temperature, Depth (CTD) sensor, ADCP/Doppler Velocity Logs (DVL), and Inertial Measurement Unit (IMU), as shown in Table 10. However, since physical components are not explicitly described and shown during the analysis, such as in PHA, identifying physical failures might not be as easy as in PHA, though similar results in terms of the reliability and maintenance aspects are obtained in the current study.

Compared to the other two methods, Procedural HAZOP does not provide a satisfactory result in terms of the reliability and maintenance aspects of the system, since the current Procedural HAZOP mainly focuses on procedures or operational sequences. Though some of the reliability-related issues can be identified, for example, a sensors issue is identified as a cause leading to the status of the AUV being incorrectly reported during the mission, and hardware failures, such as transmitter and drive board, are identified as causes leading to the failure of testing communication before operation, as shown in Table 8, Procedural HAZOP fails to provide a more detailed analysis.

7.2.2. Inclusion of the performance of software and control algorithm

For the PHA, a simple checklist-based method was employed. The level of detail of the analysis results sometimes depends on the checklist. Without a detailed checklist on software failure and interaction among components, PHA may not be sufficiently detailed to analyze the software and control algorithms' performance. Taking the hazardous event *Failure of self-designed software in AUV (No. 31)* in the PHA results, for example, the possible causes including a bad configuration and possible bugs caused by untested features, software updates, compliance issues, and insufficient functional design are identified. Apparently, the identified causes provide a general idea of how the software can fail, but without a detailed checklist on software failure, it is difficult to further refine both the hazardous event and its causes based on analysts' experience alone.

In the case of Procedural HAZOP, the current analysis mainly focuses on the operational procedure, in which the deviation is mainly related to operators' behavior. Though software failures could be identified as the causes of possible deviations, for example, the possible configuration issues leading the failure of testing communication before operation or failed detection of critical error of AUV, it is not easy to perform a more detailed analysis on how these failures occur since there are no specific guidewords on software failures to facilitate it. Other studies, however, claim that the combination of traditional HAZOP, human factor HAZOP, and software HAZOP might help to identify more software-related hazards, though further work is required (Sultana et al., 2019).

Compared to traditional methods, STPA needs a hierarchical control structure to demonstrate the system's interaction. By breaking down the entire system and identifying the relationships in this way, it is easier to identify the software failure by analyzing how UCAs can occur. As shown in Tables 9 and 10, a hazardous event may occur if the navigation system module provides the unacceptable inaccurate estimated position and heading during the mission. Though necessary inputs are received by the routing and planning module, failure can still occur when the estimation algorithm fails to provide a correct value of the estimated position and heading. Further reasons can be identified as either flawed control algorithms, such as untuned parameters in the code, or the algorithm's inability to handle navigation error well. This analysis process is guided in the STPA method when developing a loss scenario by analyzing how the process model and feedback can lead to the potential loss.

7.2.3. Inclusion of the performance of the interaction between software and hardware

System failures can occur not just because of pure hardware failure or software failure. The performance of the software sometimes depends on the hardware. Considering that the hardware may change with the impact from an environment, the complexity of a system with both software and hardware may increase. The failure caused by the interaction between software and hardware, such as the physical damage of hardware components caused by the electronic stress induced by software execution, also needs to be identified (Feng et al., 2014; Zhu and Pham, 2019). Failure caused by the interaction between software and hardware is not easy to identify due to few historical records and previous experience. The current analysis results do not identify any related hazards, but this may be because of the limited experience and knowledge of the analysis group. A detailed analysis of this aspect should be conducted in the future.

7.2.4. Inclusion of the performance of the interaction between AMS and external supporting system

In the current study, only the navigation buoys system is considered as an external supporting system for the AUV operation. In the current AUV under-ice operation, the navigation buoys system is essential to support the AUV navigation and operators' control and monitoring. As shown in the PHA results, hazards related to the AUV and navigation buoys are analyzed separately. Though the interaction between the AMS and the external supporting system is not explicitly described in PHA, the method considers this issue in another way. For example, navigation buoys drifting out of the operation area due to strong wind or current (No. 58 and No. 61) are identified when analyzing the risk caused by environmental hazards.

A similar risk is identified in the interaction between the AUV and navigation buoys system in STPA. A buoy out of the acoustic range due to ice drift causes navigation buoys not to be appropriately placed. This thus causes the position of the buoys not to be updated successfully, leading to the occurrence of *Navigation system module provides (unacceptable) inaccurate estimated position and heading during the mission* (UCA5-P-1). Though similar results might be obtained in PHA and STPA, visualizing the interaction between the AMS and the external supporting system in STPA's control structure and analyzing the interaction explicitly provides operators with a clearer view. The visualization of the interaction between the AMS and the external supporting system is very valuable in the analysis of AMS operation, in which these interactions might bring more issues compared to the operation of traditional marine systems, and therefore require special attention from operators.

7.2.5. Inclusion of the performance of the communication between the AMS and environment

Environmental hazards are explicitly described as one of the main hazards in PHA, as shown in Table 6. Possible environmental hazards identified in PHA include the strong wind, water current, existence of ice, temperature and salinity of water, wave, etc. At the same time, the system boundary used for STPA analysis usually includes the parts of the system over which the system designers have some control, according to the STPA Handbook (Leveson and Thomas, 2018). Therefore, the environment is not directly regarded as part of the system due to its uncontrollability in the current analysis, and environmental hazards are indirectly identified as the causal factors of UCAs in STPA. Since the under-ice operation is planned in the Arctic, analyzing and listing environmental hazards explicitly might be better for operators concerned with the environmental impact on the systems. Obviously, this should be taken into consideration for the operation in harsh environments when performing risk analysis.

Procedural HAZOP does not perform well when directly analyzing the interaction between the AMS and the environment. However, compared to the other two methods, it provides a much more complete and detailed analysis of how the environment affects the functioning of operators, which might then affect the operation and performance of the AUV. For example, during the deployment stage, the weather condition may cause operators to have insufficient time to deploy the AUV or navigation buoys, which in turn may lead to reduced mission time or reduced navigation coverage of buoys. This hazardous event, captured by Procedural HAZOP, is ignored in PHA and STPA. It can be shown that, compared to PHA or STPA, Procedural HAZOP can provide some new ideas in terms of the environmental hazards.

7.2.6. *Inclusion of the hazards and possible changes in risk models caused by adaptive autonomy/mode or the change of subsystems involved*

The current AUV under-ice operation task does not involve the adaptive autonomy/operation mode, so argument using analysis results is impossible in the present study. However, previous studies may provide some ideas. Yang et al. propose a systems-theoretic approach based on STPA to deal with the marine system with dynamic autonomy, in which the transition between two modes is emphasized. The possible UCAs due to the transition are analyzed by adapting four ways in which a control action can be unsafe in STPA (Yang et al., 2020b), demonstrating the applicability of STPA in terms of adaptive autonomy. PHA and HAZOP might be able to be adapted to consider this; however, little research has been done on this so far.

7.2.7. *Inclusion of the human–machine interaction*

As shown in the results, eight hazardous events related to human operators are identified in the PHA analysis, mainly focusing on task planning, maintenance and testing of both hardware and software, remote monitoring and control during the operation, and system design. However, similarly to the software failure, it is challenging to further refine the analysis without a specific hazard list related to human–machine interaction. STPA describes operators as part of the control structure system, as shown in Fig. 3, and the interaction is represented as control actions and feedback. Compared to the results obtained from PHA, STPA performs much better in identifying and analyzing the interaction between operators and the navigation buoys system. During operation, the navigation buoys system is used to transfer some control actions from the operators to the AUV and feedback from the AUV to the operators. The PHA results ignore this intermediate system when analyzing the interactions between the operators and the AUV. In contrast, the interaction between the operators and the AUV and the interaction between the operators and the navigation buoys system are separately represented in STPA, providing a more detailed analysis.

With the help of a detailed operational procedure, different operation phases from pre-deployment to post-deployment are considered in Procedural HAZOP. By analyzing the way the operations deviate from the designed procedure, it is possible to identify how the human operators' behavior affects the AUV operation, and how the issues in the AUV affect the decision-making of the human operators and thus the subsequent operations. For example, when operators are unfamiliar with the operational procedure, it may take a longer time to test or deploy AUV and buoys than expected, which can cause a delayed mission and a possible unacceptable collected data due to limited operation time. On the contrary, if AUV gets stuck under ice or one of buoys is frozen in the ice, human operators need longer time to recover the AUV or buoys due to increased difficulties. The subsequent mission may then be affected due to limited operation time or the damaged AUV or buoys from the difficult recovery.

It is found that focusing on the operational procedure, the Procedural HAZOP results provide a more detailed view of human behavior, which neither PHA nor STPA covers well. In addition, as claimed by Utne and Schjølberg (2014), certain phases of AUV operations in the Arctic may involve a higher level of risk to humans, such as during the launch and recovery of the vehicles. Procedural HAZOP separates the operation into several phases, providing a clearer view of the hazardous events during each phase. This may make it the preferred method for those operators who are concerned with certain dangerous operational phases. However, challenges may arise if the designed procedure is not valid for the operation. The hazardous event caused by this might be difficult to identify during the analysis.

7.2.8. *Inclusion of the security issue*

In the current study, none of the three analysis methods considers security. This is not due to these methods' inability, but because of the research scope and type of operation in the current case study. A Security Vulnerability Analysis (SVA) is quite similar to a PHA and HAZOP, in terms of procedure and documentation. An SVA evaluates risk from deliberate acts resulting in accidents or incidents. Thus, an existing PHA or HAZOP can be efficiently and effectively expanded to add SVA to include the possible security issue (Nolan, 2014). An example can be found in Thieme et al. (2019), where security and cybersecurity are included in a PHA of an auto-ferry operation. An extension of STPA, called STPA-SEC, was proposed to solve the security issue (Leveson, 2004). Several studies have been conducted using STPA-SEC for security analysis (Sayers et al., 2020; Schmittner et al., 2016; Sidhu, 2018), and the results have proved its validity in solving security issues. A method's ability to solve security issues is also related to its ability to assess the software and control algorithms' performance (see Sections 7.2 and 7.3).

7.2.9. *Inclusion of various sources of data to estimate the risk level*

All three methods gather different knowledge in the analysis, including historical data, expert experience, and specific design information of the current AUV and navigation buoys system. Still, none of them provide real-time quantitative estimations of the risk level, which does not make use of sensor data. However, they can help identify which data should be collected and utilized to construct an online risk model. For example, monitoring the distance between navigation buoys during the operation might be necessary to improve the safe operation of the AUV. This conclusion can be derived from the hazardous events No. 58 and No. 61 from the PHA analysis. Hazardous events identified in Procedural HAZOP, such as *Operators do not/unable to test acoustic communication between buoys and AUV*, also show the necessity to monitor the distance between navigation buoys during the operation. A similar conclusion can be drawn from several of the UCAs identified in STPA, including UCA5-P-1 (Navigation system module provides (unacceptable) inaccurate estimated position and heading during the mission), UCA17-N-1 (Navigation system module of AUV does not measure the range between the vehicle and the buoy when the vehicle is operating under water), UCA18-N-1 (Navigation buoys system does not provide the position of buoys to AUV when the vehicle is operating under water), UCA19-N-1 (AUV operator does not stop the mission when the AUV mission is found to have failed) and so on.

7.2.10. *Level of knowledge needed for analysis*

The PHA should be carried out by those who have a background in safety engineering, and it requires experience and understanding of the system. A HAZOP study is carried out as several brainstorming sessions by a group of experts. Compared to PHA and HAZOP, the development of STPA requires more experience with the method. For example, the STPA analysis results rely heavily on the quality of the control structure in step 2. The development of the control structure depends on the analyst's knowledge of the system and the ability to conceptualize the system. In general, STPA needs sufficient knowledge to build the structure and identify UCAs. Based on the experience in the current study, both PHA and HAZOP were less time-consuming than STPA. When knowledge and time are limited, PHA or HAZOP are probably good choices with acceptable analysis results.

7.2.11. *Be able to update risk level with new information/data*

All these three methods are qualitative or semi-quantitative risk assessment methods. PHA and HAZOP may use a risk matrix to generate a basic ranking of risk values, providing operators with information about which part of the system or indicator is more important than others, as well as the information that needs more attention for monitoring. This can help risk analysts determine what kind of new data should be collected and then to further develop a dynamic model based on these indicators, thereby updating the risk level with new information.

One of the limitations of STPA is that it cannot provide a quantitative risk measurement. Though it might provide more nearly complete analysis in terms of software failure and the interaction among components as discussed in previous sections, operators might be overwhelmed by a long list of loss scenarios without knowing their severity. Therefore, it is challenging to know which information should be prioritized for monitoring and then updating.

7.2.12. *Be able to deal with emerging risks*

Though various definitions are given in different studies, the concept of emerging risk is usually associated with new (types of) events and related to known unknowns (Flage and Aven, 2015). In the operation of an AMS, emerging risks might occur due to several factors, including (Wróbel et al., 2018a):

1) The level of detail of the analysis is relatively low when the operational experience is limited, such as the operation of MASS (Chaal et al., 2020; Wróbel et al., 2018a, b) and under-ice operation of AUVs, causing only general statements to be made.
2) The complexity of the system and the nature of the interaction between its components lead to multidirectional failure propagation that analysts cannot identify.

PHA and STPA can be used to evaluate hazards early in a project being undertaken at the conceptual stage and can be refined later through additional and more thorough studies. For example, as more details of the AUV or navigation buoys system in this study are accessible, a more detailed list of components can be provided when analyzing technical hazards in PHA, and a more detailed control structure in STPA can be used to obtain a more detailed description of the control actions and feedback. In terms of the complex interaction in the system, the ability to handle this issue has been discussed in previous subsections. Hence, it can be concluded that STPA can provide a better analysis than PHA and HAZOP.

All three methods, however, are unable to guarantee that all potential hazardous events and scenarios can be addressed. A general challenge with hazard identification is that there is no or little feedback. Analysts might miss an unidentified hazard until it occurs, and the consequences may turn out differently. The monitored data is expected to provide some pre-warning or feedback to the risk analyst, helping to deal with emerging hazards.

7.2.13. *Be able to efficiently identify RIFs that need to be monitored online or in real time during operation*

Results from the three methods can be used to identify RIFs that can be used in the development of the online risk model. Though monitored RIFs can provide a measurement of an online risk value, it is almost impossible to monitor all identified RIFs due to challenges with quantification and costs. Determining which RIFs should be prioritized is therefore essential.

As discussed in Section 7.11, compared to PHA and HAZOP, STPA might provide an overwhelming list of input to deriving RIFs that operators cannot easily handle due to the difficulties in ranking the importance of loss scenarios. A specific risk model focusing on the RIFs that are derived from several UCAs of interest, such as the model developed by Utne et al. (2020), might be solvable; however, providing the overall risk spectrum of an AMS using the RIFs derived from the full list of UCAs in STPA can be challenging.

7.2.14. *Be able to effectively model the correlation between identified RIFs*

None of the three methods quantitatively describes the correlation among RIFs like FTA or BBN. However, the analysis logic behind these methods might be able to help quantitatively identify the correlation among them in constructing an online risk model in the next stage.

In STPA, the results are provided in a top-down manner. The UCAs identified are used to develop loss scenarios, and a more detailed analysis can be performed to refine the possible loss scenarios. Rokseth et al. (2018) represent this refinement process of loss scenarios as a tree structure. Through this tree structure, the relationship among RIFs can be preliminarily determined. This top-down process of STPA results can be transformed and represented using FTA or BBN, as demonstrated in previous studies by Bolbot et al. (2020) and Utne et al. (2020). Given the preliminary relationship determined in STPA, statistics or expert judgment can be used to further determine the detailed correlation among identified RIFs in the online risk model.

Developing a quantitative risk model based on PHA and HAZOP requires analysts to fully understand the hazards and their potential effects from the analysis. It is not easy to determine the correlation among identified RIFs without a structured way to show the results, which may be easier with the control hierarchy in STPA. Even with a list of hazardous events including causes and consequences as in PHA, analysts still need to extract the necessary information from the results and then determine the relationship among the identified RIFs.

7.2.15. *Be able to deal with the uncertainty*

Online risk models rely on real-time monitoring to estimate the risk level of the system. Therefore, the sensor and data fusion algorithms' uncertainty can significantly affect the accuracy of online risk models. Although the methods identify hazards associated with sensors such as the CTD sensor and navigation sensors, the existing sensors in the AMS might be insufficient to provide the whole online risk picture. Other kinds of data might be required to further construct the online risk model, and other new sensors might also be needed. The risk caused by these sensors and data fusion algorithms should be accurately measured and reflected in the future online risk model.

7.3. *Verification and validation*

The verification and validation of hazard identification results are always a challenging issue since the process of hazard identification and risk analysis often needs multiple iterations to improve the accuracy and completeness of the results. Also, these analyses often address incidents for which there is limited experience with. However, considering the following points, the analysis results and the derived conclusion in this study can be considered acceptable and credible to a certain extent.

Firstly, three methods used in the current study have been widely used in hazard identification and risk assessment. Many previous studies have tested their effectiveness and validity (Rokseth et al., 2017; Sultana et al., 2019). Also, PHA and HAZOP have been widely used and proved in industries such as oil and gas industry and marine and offshore industry (Rausand, 2013). The well-structured steps in these methods make it easy for them to provide reasonable results. In the current study, PHA and Procedural HAZOP are methods that based on brainstorming sessions, and STPA is also performed based on researcher's experience. The quality of the analysis mainly depends on the knowledge from different expert and historical experience. Researchers in the analysis group have a good knowledge in AUV and have many years of experience in operating AUV under different environmental conditions, which can help to provide an acceptable and credible results.

In addition, the hazard identification results from three methods demonstrate good agreement with the analysis results in other studies and historical operation and fault log reported in previous AUV operations (Brito et al., 2010; Ferguson, 2008; Kaminski et al., 2010). For example, according to the fault log reported in the study by Brito et al. (2010), the aborted mission due to bad crimp joint has been detected in a previous AUV operation, which is also identified in the current PHA results; the mission failure caused by uncertainty in indicated motor rpm is also identified in the current STPA results. Some identified hazards that specific to the AUV operation in harsh environment are also found in previous AUV operations in the Arctic. For example, the failure of equipment during deployment, such as CTD sensor, caused by the large temperature gradients in the air and underwater (Ferguson, 2008; Kaminski et al., 2010), which has been identified in the PHA and Procedural HAZOP results.

However, due to the limitations of researchers' knowledge and the shortcoming of applied methods in certain aspects, the current study cannot guarantee all hazardous events related to AUV under-ice operation are identified. Regular updates and improvements should be made to improve the accuracy and completeness of the results in the future.

In terms of the conclusion derived in Section 7.2, all the points and opinions are generalized from the analysis process of three methods. Detailed examples in the analysis results are provided in this section to prove and support the point of view from researchers. However, the changes in the input to the analysis do affect the derived conclusion. The main essential influencing factors include the available information or historical data of the studied system and analysts' knowledge of the studied system. In order to reduce the influence of the change in these factors, the same analysts were involved both in PHA and Procedural HAZOP workshops; STPA analysis was initially performed by the first author and then reviewed by the same analyst as the PHA and Procedural HAZOP workshops. In terms of the possible influences of the selected case study on the conclusions drawn, although the AUV under-ice operation is used as a case study, many attributes and characteristics are shared by other AMS. In addition, since the criteria developed in the current study are more or less generic, it is expected that the analysis results and conclusion could be adapted to other AMS as well.

8. Conclusions and future work

The current study identifies criteria that reflect the aspects that should be considered when developing an online risk model for AMS, and these criteria may also be used as a checklist to verify and improve the existing analysis results. The current work investigates how PHA, STPA, and Procedural HAZOP contribute to fulfilling the different requirements for online risk modeling of AMS, and how the results may be used as the basis for model development.

The case study in the article addresses an AUV under-ice operation in the Arctic. Considering the challenges in underwater navigation, the online risk model should mainly focus on the interaction between the AUV and its navigation buoys system and also the behavior of human operators during the operation.

Considering that most AMS have similar requirements and demands as AUVs with respect to the online risk model, the analysis results and conclusion from the current study can also be adapted to other AMS. Generally, the analysis results show that, compared to the other two methods, STPA is considered a good basis for developing an online risk model in terms of the number of criteria fulfilled, and especially its ability to handle the interaction among systems and software failure, although some disadvantages prevent it from becoming an ideal one.

A challenge with using STPA is the difficulties in determining the RIFs that should be included and monitored in an online risk model based on the exhaustive list of unranked loss scenarios. Considering its relatively good coverage of identified evaluation criteria, however, and that some of the RIFs may be difficult to measure in operation even though they are important in the case of AMS, such as the performance of software and control algorithm, it is worth considering STPA as a basis for the further development of online risk models. In addition, considering the changing role of human operators in the operation of AMS, it is necessary to identify specific RIFs related to human operators in the operation of AMS. Hence, some of the disadvantages with STPA may be mitigated by using PHA and Procedural HAZOP as complementary tools. In future works, the results obtained from these three methods will be used to develop an online risk model for the AUV operation. The criteria identified for the online risk model of AMS in the present study will also be used as a checklist to verify and improve the quality when developing the online risk model.

CRediT authorship contribution statement

Ruochen Yang: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Ingrid Bouwer Utne:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

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 3

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Dynamic Risk Analysis of Operation of the Autonomous Underwater Vehicle (AUV)

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The autonomous underwater vehicle (AUV) plays an essential role in scientific research and offshore exploration. Numerous risk issues exist during operation, however, which makes the AUV mission risky. The operating environment is one of the factors that seriously affects its safe operation. In long-range AUV missions, unavoidable changes in the operating environment impact the vehicle risk. Therefore, it is critical to determine the effect of the dynamic environment on AUV operation. The current work aims to provide a method for assessing the risk of AUV operation, considering the effect of changes in the operating environment. In this study, the Bayesian approach is applied, capturing various potential risk factors and their relationships. In order to take the influence of environmental changes on the AUV missions into account, the study applies a dynamic Bayesian network to incorporate online location information. Given the online information of the AUV´s operating environment, a dynamic risk value can then be analysed and determined. The proposed method provides operators with an overview of the environmental impact on AUV operation. It can work as a guide on how to choose the mission path before the operation, and it also provides the vehicle and operators with a dynamic risk indicator, which can support the AUV's decision making.

Keywords: Dynamic risk analysis, autonomous system, autonomous underwater vehicle (AUV), dynamic Bayesian network (DBN), operating environment

1. Introduction

Autonomous Underwater Vehicles (AUVs) deployment and research are currently getting increasingly popular. An AUV is a marine robot device that can be operated underwater with little or no human intervention required (Paull et al. 2018; Sahoo, Dwivedy, and Robi 2019). While the use of manned vehicles for underwater exploration may pose risks to humans, unmanned underwater systems, such as AUVs, can be used for explorations in hazardous underwater environments. However, numerous risk issues exist during the operation of the AUV.

Several previous studies have been conducted to analyze the risk of autonomous marine systems. Loh et al. (2019) conducted a risk assessment for AUV under-ice mission. The research aimed to explore the risk issue of the AUV mission in a harsh environment. Historical fault log data, as well as expert knowledge, were used in the study to develop a risk model. Hegde et al. (2018, 2019) developed dynamic safety envelopes for autonomous remotely operated vehicles (ROV). In these studies, the Octree method was used to set up the cuboidal shape of the proposed safety envelope, while the size of the dynamic safety envelope was determined by modeling a fuzzy inference system. To assess the reliability of AUVs, Brito and Griffiths (2011) applied a Markov chain model to capture the different states of the AUV operation. Step sequence from prelaunch to operation to recovery were included in this study, and 11 discrete states were identified in total. A case study using the fault history of the Autosub3 AUV was conducted to provide the information for different operation phases. In another study by Brito and Griffiths (2016), the Bayesian approach was used to predict the risk of AUV loss during their missions. The research

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aimed to provide a rigorous procedure for AUV risk management in hazardous environments.

Among the factors that contribute to the risk of the AUV operation, the operating environment can significantly affect the operation. Previous studies have demonstrated that the different operating environments can bring the AUV operation into varying levels of risk (Brito, Griffiths, and Trembranis 2008; Brito, Griffiths, and Challenor 2010). For long-range AUV missions, which typically are operations lasting hundreds of kilometres, even up to one thousand kilometres, it is highly probable that the vehicle experiences several different environments, and these environments can bring various types of hazards to the operation. Therefore, for safe operation, it is necessary to capture the different hazards and determine the dynamic risk of AUV operation during the mission over time and then take corresponding actions or pay more attention during high-risk periods. There is, however, limited information and control of the AUVs in the current operations.

In this study, a dynamic Bayesian network (DBN) model is applied to capture the change of the variables over time. The software, GeNIe, is used to construct networks and analyze the risk of AUV operation. A DBN is an extended Bayesian network with some additional mechanisms to capture the temporal relationship between variables (Murphy and Russell 2002; Amin, Khan, and Imtiaz 2018). A DBN can also be regarded as a first-order Markov model, while the variables at time step i+1 are d-separated from the variables at time step i-1, given the variables at time step i (Madsen and Kjærulff 2013). This means that the arc between two slices only starts from one time-slice to the subsequent time-slice. Taking the influence over time into account, a DBN is a suitable tool for time series modeling.

The objective of this study is to propose a dynamic risk model of an AUV mission capturing the change of the environmental influence on AUV operation. The proposed methodology aims to provide AUV operators with an overview of the environmental effect on the AUV operation. Also, the dynamic risk value can provide operators with a risk indicator for the AUV's adaptive mission, which can help with the AUV's decision making during the mission.

2. Proposed Methodology

Fig. 1 demonstrates the flowchart of the proposed methodology. The first step is to define the mission. A mission path needs to be planned in the first place. Then, the types of potential environments that an AUV might experience along the path can be determined. This is followed by determining critical environmental factors that might affect AUV operation in each type of environment. The influence of environmental factors on AUV operation depends on the type and characteristics of an AUV, considering that a robust AUV is more reliable in a harsh environment. Therefore, this information also needs to be determined before the analysis.

During an AUV mission, the real-time location information can be obtained, either by the navigation systems on AUVs or by prediction by the pre-defined path. With the changing of the AUV's location, the operating environment of AUV changes accordingly. The environmental influence is simulated using BNs in this study, and a conditional probability is assigned in the model to represent the influence of the operating environment on the AUV subsystems, thereby resulting in different potential consequences, affecting the risk of AUV operation.

More details of the methodology are presented below.

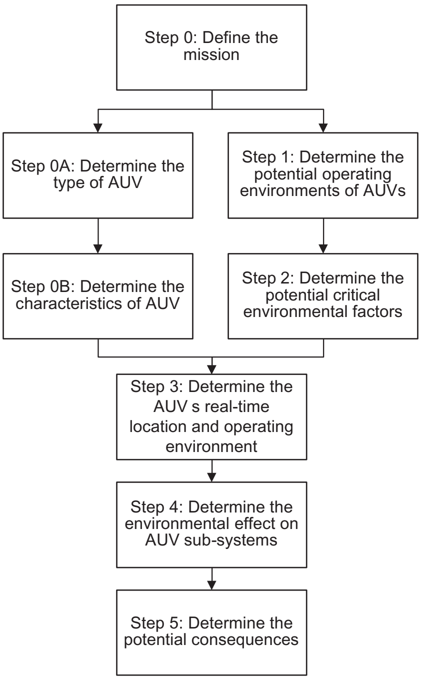

Fig. 1 Flowchart of the proposed methodology

Table 1 Environmental factors considered for each environment type

	WD	WT	ST	CV	RC	IC	IT	ShT	ES	PF
Open water	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
Coastal	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Sea ice	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No
Ice shelf	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No
Group island	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
Enclosed environment	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No

Abbreviation:

WD = Water Depth, WT = Water Temperature, ST = Seabed Topography, CV = Current Velocity, RC = Rock Concentration, IC = Ice Concentration, IT = Ice Thickness, ShT = Ship Traffic, ES = Engineering Structure, PF = Possible fishing gears

2.1 *Step 1: Determine the potential operating environments of AUVs*

In the studies by Brito et al. (2008; 2010; 2016), four potential operating environments for an AUV mission in harsh environments are defined, including open water, coastal water, sea ice, and ice shelf, and the current study follows this classification. Besides, near group islands and other complex terrains are included to make the proposed model suitable for most AUV missions.

Open waters are defined as areas far from the coast and traffic lanes (Brito, Griffiths, and Trembranis 2008). This environment allows the AUV to safely float to the water surface, to obtain a precise location through GPS. In the case of an unexpected error or emergency, the AUV can implement a safety plan and float to the water surface. For AUV operations in open waters, the hazards are few when the vehicle is in water, while other environmental factors, such as high waves, strong winds or other vessels, may cause danger when the vehicle floats on the surface (Brito, Griffiths, and Trembranis 2008). Generally, open waters provide a relatively benign operating environment for AUV operations.

Coastal waters represent the interface section between land and ocean, including waters from shelf edge and landward towards the shore (Brito, Griffiths, and Trembranis 2008). Due to the high-density ship traffic and some structures, this environment might pose a relatively high risk in an AUV operation. Possible hazards for AUV operation in coastal waters include ship traffic, divers, engineering structures, and fishing gears (Patterson, Sias, and Gouge 2000). Also, possible turbid waters and strong currents and waves in coastal waters are risk issues, especially in terms of collisions and recovery of AUV.

Sea ice and iceberg pose a variety of risks on AUV operation. For example, floating ice poses a collision hazard to AUVs, which may cause physical damage to components and subsystems of the AUV, such as propellers, sensors, and navigation systems.

When AUVs are used in Antarctic research, they usually need to be operated under ice shelves. An *ice shelf* is defined as thick floating ice attached to the land. Different from the sea ice, which is typically less than three meters thick, the thickness of the ice shelf can be up to 2000 m, while cliff edges can be up to 100 m high (Elizabeth, Charles, and Robin 1975; Wadhams 1980; Holland and Jenkins 1999). For an AUV mission in this case, it is almost impossible to recover it once some technical failures occur. Therefore, deploying AUV under ice shelves is a very challenging task.

Islands group is defined as a set of islands formed close to the coast of a continent. The seabed topology of an island group is usually very complicated. The rapid spatial and temporal change of water depth might cause the grounding of the vehicle and also the collision with rocks for the AUV mission in this environment, which requires the AUV to have a robust collision avoidance system.

Enclosed environment considered in this study includes pipes, cenotes, or lakes. The main hazard considered in this case is the potential collision with these structures or boundaries.

2.2 *Step 2: Determine the potential critical environmental factors*

Environmental factors are defined as the factors that have the potential to affect the safe operation of AUVs in this study. Given the operating environment classification defined in the previous section, environmental factors can be identified for each environment type. Potential environmental factors that need to be considered in this study include water depth, water temperature, seabed topography, current velocity, rock concentration, ice concentration, ice thickness, ship traffic, engineering structure, possible fishing gears, etc. For simplification, only factors that have a critical influence on AUV operation are considered, ignoring factors that have minor influence. Table 1 lists the environmental factors considered for each type of environment in the risk analysis, where "Yes" indicates that the corresponding factor need to be considered. In the application of this methodology, the influencing factors considered for each type of environment can be adjusted according to different missions.

2.3 *Step 3: Determine the AUV's real-time location and operating environment*

Given the potential operating environment classification and their possible influencing factors on AUV operation in previous sections, the next step is to obtain the real-time location of an AUV and determine its operating environment along the path. This process is simulated using the DBN model in this study.

In the proposed DBN model, the node "Predicted operating environment" is created to capture the operating environment type during the mission, while each type of potential operating environment is set as a single state of the node, as shown in Fig. 2 (a). Therefore, it can be assumed that the change of the state of the node stands for the change of the type of the operating environment. The circular arc from the node to itself indicates that the previous state of the node has an influence on the current state, and the number "1" on the arc indicates that the current state is only affected by the state in the last time step, ignoring the influence of states prior to that. Fig. 2 (b) shows an example of the temporal network unrolled for several time-slices. It is used to locate the state of the node in a specific time slice, and it can provide a clearer view of the relationship among the nodes in different time slices. In the DBN model, the change of the state of a specific node is considered to be a stochastic process, while the probability of the state changing of the node is simulated using a conditional probability table (CPT). For example, given the current operating environment of an AUV is open water, the probability that the operating environment is sea ice in the next time slice is modeled by the assigned conditional probability.

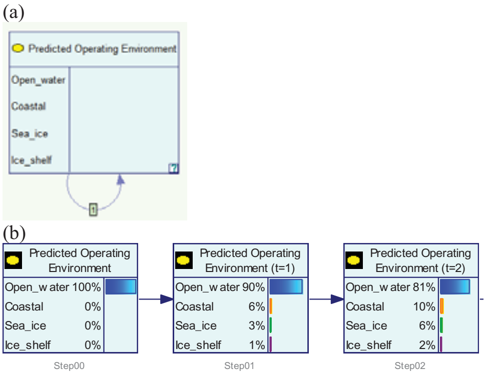

Fig. 2 Example of the DBN model of preliminary operating environment prediction

The stochastic modeling might be reasonable for the simulation of the change between two time slices. However, without new location information as input, the simulation error of the model is accumulated, and the model is unable to provide a reasonable prediction in the long run. This problem can be solved with the help of updating the predicted location information of the AUV system periodically. During an AUV mission, this information can be obtained through the navigation system of an AUV.

In the current model, the time between two slices is short, and the change is predicted by a stochastic process. The time span between two location predictions by the navigation system is long, which can be input periodically in the DBN as new evidence. Therefore, given the real-time location predicted periodically provided by the navigation system, together with the stochastic simulation between two time slices, the real-time operating environment of the vehicle can be determined.

Even though the study of underwater navigation has rapidly developed in the last decade, the uncertainty of location prediction still remains in various navigation methods. Hence, the uncertainty caused by the environment needs to be considered. In the proposed model, the "Actual operating environment" node is added and considered to be influenced by the predicted environment as well as the uncertainty caused by environments. A new node "Prediction uncertainty" is introduced in the BN, and it is assumed to be only affected by the operating environment. The uncertainty is classified as three degrees, from low to high, in this study. Given the operating environment predicted, the uncertainty of the information prediction caused by the environment can be determined by expert judgment. For example, when the AUV operates under ice, the GPS system does not work because it is unable to send signals through water. Relying on other navigation methods can lead to a relatively high uncertainty in the location prediction of an AUV. In this way, the operating environment in each time slice is predicted, which provides real-time information about the operating environment and can be used in the risk analysis.

2.4 *Step 4: Determine the environmental effect on AUV subsystems*

The influence of the identified environmental factors on the AUV subsystem is simulated using BNs in this step. The CPTs are assigned mainly based on expert knowledge to quantify the environmental factors' influence on the failure of each AUV's subsystem, which contributes to the further loss of the whole AUV system. In this study, undesired events are believed to be caused by the failure of corresponding subsystems of an AUV.

Different from other influencing factors, sometimes environmental factors have an "accumulative" effect, which means that when an AUV stays in a high-risk environment for a long time, it may experience higher risk than if it stays in this environment for a short time. For example, for an AUV operating under ice, the low temperature and other factors may pose a risk to its safe operation, such as the effect on battery capacity, and the degradation caused by this effect will increase over time It might be acceptable for an AUV to stay for a short time; however, the risk increases when it stays for a longer time. When quantifying the online risk value of AUV operation, this issue should be considered and addressed.

In the current model, this issue is addressed by introducing an indicator node called "Time span influence". This node records the operating environments in several previous time slices and outputs an indicator value to the network. It contributes to the failure of subsystems, together with environmental factors.

In this study, the influence of the environment from the previous three time slices are considered, ignoring the influence of earlier time slices. Given the previous information of the operating environment, the indicator "Time span influence" in a specific time slice "n" can be determined as $\mathrm{P}(\mathrm{TS}_{\mathrm{t}=n} \mid \mathrm{OE}_{\mathrm{t}=n-3}, \mathrm{OE}_{\mathrm{t}=n-2}, \mathrm{OE}_{\mathrm{t}=n-1})$, where TS stands for time span influence, and OE stands for operating environment information in a different time slice.

2.5 *Step 5: Determine the potential consequences*

In this study, four undesired events are identified to model the potential failure consequence of the AUV operation: mission failure, loss of data or unsatisfied data, damage of AUVs, loss of AUV.

Mission failure is defined as the vehicle's inability to complete its mission, or the mission is aborted automatically due to safety issues. Various causes to mission abortion, according to the fault log in the study by Brito et al. (2008; 2016), including the failure of the network, over depth, etc. Damage of AUVs is defined as the physical damage of AUVs. The loss of AUVs refers to the unsuccessful recovery of AUVs, which is considered to be caused by poor communication between the vehicle and operators and the damage of the AUV subsystem, such as power system, propulsion system, etc. Communication between the vehicle and the operator/supervisor is affected by the operating environment. For AUV operations in most environments, the AUV will float to the surface if a mission is aborted or a failure is detected, which allows communication between the AUV and the operators. However, in some environments, such as the under-ice mission, communications are almost impossible. Therefore, the failure of subsystems and poor communication may lead to the loss of AUV.

3. Case Study

3.1 *Operation scenario*

A case study is conducted in this section to show the application of the proposed method. The risk analysis of a previous AUV operation in the Antarctic is applied, based on the study and data from Brito et al. (2010; 2016) and Mcphail et al. (2009).

On January 5, 2009, the U.S. ice breaker, the Nathaniel B. Palmer, with AUV Autosub3 onboard departed Punta Arenas, Chile, for Pine Island Glacier, Antarctica (Brito, Griffiths, and Challenor 2010). Several under-ice AUV missions were performed during this cruise. The objective of these missions was to investigate the shape of the ice shelf, the sea bed bathymetry, the currents, and the physical oceanography within the ice cavity (McPhail et al. 2009).

The AUV used in this mission was Autosub3 AUV. This AUV is 6.8 m long and 0.9 m in diameter. It can be operated in 1600 m depth underwater, and the battery can allow the vehicle to operate up to 350 km at the speed of 1.5 m/s (McPhail et al. 2009). According to the planned path of the mission 434, the AUV was launched from point 1, -102.003 ° longitude, -75.007 ° latitude, which is open water, and then moves towards ice shelf through sea ice section. The total operation time was over 24 hours, and the AUV stayed under the ice shelf for about 12 hours. Detailed events description of this mission can be found in the study by McPhail et al. (2009).

Risk analysis of the AUV mission

Fig. 3 shows the entire DBN structure of the current case study using the proposed methodology. In the case study, three potential operating environments are determined, including open water, sea ice, and ice shelf.

The initial operating environment is open water, which is represented as P(Open water) =1 when t=0. The change of environment over time depends on the stochastic process simulation as well as updated information from the navigation system and the operators' prediction, as discussed in Section 2.3. Table 2 shows the CPT for the node of "Predicted operating environment". This is used to assess the change of operating environment between two time slices. The conditional probabilities are assigned based on expert knowledge. The assigned CPT accounts for the fact that, given the operating environment of an AUV in the current time slice, it is most likely to stay in the same operating environment in the next time slice, and it is also possible to travel to another type of environment with a relatively lower probability. In the application of the proposed methodology, the location prediction is assumed to be obtained and input in the model as evidence every 30 mins, which is assumed to be five time-steps in this case. Therefore, each time step is 6 mins. According to the study by McPhail et al. (2009), the vehicle is assumed to be in open water before t=25, and at t=30, it enters the sea ice region, and then enters the ice shelf when t=45 until t=240. During the time step between t=45 and t=240, the AUV is assumed to stay under the ice shelf for the exploration mission. The AUV leaves the ice shelf for sea ice when t=245 and enters the open water region when t=265 until the end of the mission. The total simulation time step is 325 in this case study.

Table 2 CPT for the node of "Predicted operating environment"

	Open water (t-1)	Sea ice (t-1)	Ice shelf (t-1)
Open water (t)	0.9	0.1	0.01
Sea ice (t)	0.07	0.8	0.14
Ice shelf (t)	0.03	0.1	0.85

Table 3 presents the assigned CPT to determine the uncertainty caused by each type of environment. The conditional probability is assigned based on expert knowledge. While the uncertainty in open water is low due to relatively accurate navigation, the uncertainty under the ice is increasing rapidly due to limited communication and relatively inaccurate underwater navigation. The actual operating environment is determined by combining the predicted operating environment and prediction uncertainty, as shown in Fig. 3.

Table 3 CPT for the node of "Prediction uncertainty"

Uncertainty	Open water	Sea ice	Ice shelf
Low	0.9	0.25	0
Medium	0.1	0.5	0.1
High	0	0.25	0.9

Given the operating environment determined, corresponding influential factors can be determined according to Table 1. Considering the operating environments in this case, a total of seven environmental factors need to be considered. They are water depth, water temperature, seabed topology, current velocity, rock concentration, ice concentration, and ice thickness. In addition, eight subsystems are defined as principal parts of an AUV, including the propulsion system, power system, navigation system, communication system, sensors, obstacle avoidance system, cybernetics and emergency system. Environmental factors can contribute to the failure of subsystems of an AUV. For example, the failure of sensors is believed to be influenced by ice concentration, water temperature seabed topology and rock concentration. The corresponding CPTs are derived based on expert knowledge.

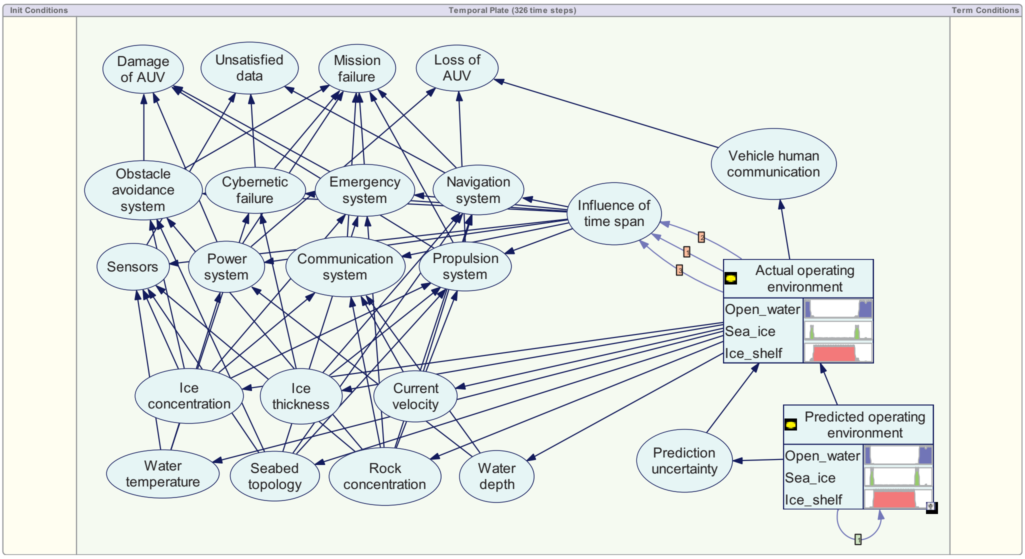

Fig. 3 DBN structure of the case study

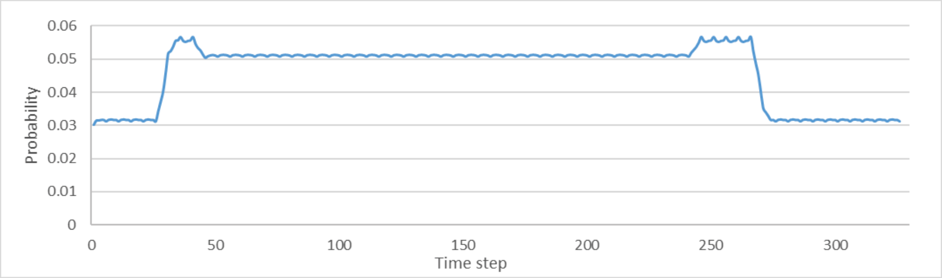

Fig. 4 Results of "Damage of AUV" in the risk analysis of the AUV operation

Four undesired events are considered as potential consequences, as mentioned in Section 2.5 and shown in Fig. 3. The failures of different subsystems are believed to influence the occurrence of these events. For example, as shown in Fig. 3, the damage of AUV is believed to be caused by the failure of the obstacle avoidance system, power system, and emergency system, while the unsatisfied data is caused by the failure of sensors, the navigation system, and cybernetics.

3.2 *Result and discussion*

For the safe operation of AUVs, it is necessary to assess the result of four undesired events as potential consequences. Due to space limitation, the result of the event "Damage of AUV" is shown and discussed as an example in this section.

Fig. 4 shows the result of "Damage of AUV" in the case study. The probability of the undesired event changes over time, reflecting the situation of the AUV in different operating environments. According to the result, the risk increases rapidly when the vehicle enters the sea ice region. After a short period of staying in the sea ice region, the vehicle is believed to enter the ice shelf and start the exploration. The probability decreases a bit during the under-ice exploration. Since the operating environment does not change during this period, the probability of the damage of AUV remains at a relatively stable stage. When the vehicle leaves an ice shelf for the sea ice region, the probability increases due to the existence of floating ice. Then the probability decreases by almost half when the vehicle returned to the open water region.

In general, the probability of mission failure is relatively high when the vehicle enters the ice region according to the results. The dynamic risk model provides a clear view of the AUV situation to AUV operators, allowing AUV operators directly to obtain the online risk value of AUV. This can remind operators to pay more attention during dangerous times and do some preparation to prevent potential failures.

4. Conclusion

The current study proposes a methodology for dynamic risk analysis of long-range AUV operation using DBN. Different operating environments are considered in the methodology, including open water, coastal water, sea ice, ice shelf, island group, and enclosed environment. In the case study, the result of the damage of AUV is shown and analyzed as an example. The result demonstrates that the proposed methodology can provide AUV operators with a clear view of online risk during the AUV mission.

For mission planning, the current study can serve as a tool to determine the preliminary risk value. Operators can use it to decide which path is most appropriate for the AUV mission beforehand by assuming the possible location change of AUV during the mission. During the mission, the dynamic risk value can serve as an indicator for the AUV operator to monitor the vehicle's status and determine whether a safety plan needs to be taken when the risk value is unacceptably high. In addition, the proposed method provides a quantitative value of risk it can also serve as a risk indicator for the AUV's adaptive mission, which allows AUV to avoid the hazardous environment automatically.

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Article 4

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Dynamic maintenance planning for autonomous marine systems (AMS) and operations

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Abstract

Compared to conventional marine systems where the crew onboard can perform maintenance frequently and flexibly, only a limited or no crew will be involved during the voyage of the autonomous systems, which challenges maintenance planning and execution. The current study therefore identifies the relevant issues and proposes to solve these through a dynamic maintenance planning method.

A dynamic maintenance planning method is developed for AMS. Considering economical dependencies among components, the study presents a dynamic grouping method to determine the optimum maintenance opportunity for the AMS from future expected opportunities. Stochastic dependencies of components are considered by using the Markov model. A multiphase Markov model is proposed for modelling stochastic dependencies between components where the limited and irregular maintenance opportunities are handled by the multiphase part of the model. A heuristic is proposed to deal with the combinatorial challenge.

To demonstrate the application of the proposed method, the maintenance planning of a cooling system of an autonomous ship is performed in the case study. To validate the performance, the proposed heuristic is compared with existing "short sighted" methods for selection of candidate groups for maintenance. In the validation, various scenarios with different component states and maintenance strategies are tested.

Keywords: Maintenance Planning; Autonomous Marine Systems (AMS); Autonomous Ship; Maintenance Grouping; Markov Model

Notation

$z_{i_j}(t)$	Failure rate of component i_j
S	Set-up cost
C_i^P	Planned maintenance cost of any component in subsystem i
$C_{i_j}^U$	Unplanned maintenance cost of component i_j;
C_i^{sc}	Specific failure-repair cost of any component in subsystem i
$C_{i_j,\mathrm{sys}}^u$	System shutdown costs caused by the failure of component i_j
C_{sys}^r	System recovery costs

$C^{d}_{i_j,\mathrm{sys}}$	System downtime costs
$C^{\mathrm{DT}}_{\mathrm{sys}}$	System downtime cost rate
$\lambda_{E,i_j}(x)$	Effective failure rate of the component i_j in a period $[0, x)$
$M_{i_j}(x)$	Accumulated expected costs due to failures in a period $[0, x)$ for component i_j maintained at time 0, exclusive planned maintenance cost
k	Number of components sharing the set-up costs
$C^{EU}_{i_j}(t)$	Expected unplanned cost of component i_j in the period $[t_0, t)$
x_{i_j}	Current age of component i_j at the time t_0
$x^{*}_{i_j}$	Optimum maintenance interval of component i_j
$\Phi^{*}_{i_j}$	Minimum average costs per unit time when component i_j is optimized individually
T	Planning horizon
$C^{\infty}_{i_j,Cr}(t)$	Total costs of component i_j after scheduled maintenance at time t until the planning horizon
$C_{Cr,i_j}(t)$	Total maintenance cost of a critical component i_j with the next planned maintenance time at t
λ_{i_j}	Transition rates in the Markov model, caused by the failure of component i_j
$\lambda_{i_j,high}$	Transition rates in the Markov model, caused by the failure of component i_j, given that the other component in subsystem i has already in failed state.
μ_i	Repair rate of any component in subsystem i
$\mathrm{DT}_i(t_1, t_2)$	Expected downtime during the period from t_1 and t_2 for subsystem i
$P_m(t)$	Time-dependent value of the probability that subsystem i is in State m at time t
$\nu_{i,0}(t_1, t_2)$	Expected number of times that subsystem i visits State 0 between time t_1 and t_2
$C_{f,i}(t_1, t_2)$	Expected failure cost caused by subsystem i between time t_1 and t_2
${\lambda_{i_j}}'$	Transition rates in the second phase of multiphase Markov model, caused by the failure of component i_j
${\lambda_{i_j,high}}'$	Transition rates in the second phase of multiphase Markov model, caused by the failure of component i_j, given that the other component in subsystem i has already in failed state.
$\nu_{i,12\rightarrow 3}(t_1, t_2)$	Expected number of times that subsystem i transfers from either State 1 or 2 to 3 between time t_1 and t_2
$C^{\infty}_{i_j,KooN}(t)$	Total costs of component i_j (in KooN system) after scheduled maintenance at time t until the planning horizon
t_{Hbr}	Time point of next scheduled maintenance harbor
$t^{*}_{i_j}$	Global optimum maintenance time of component i_j
$C_{f,i_l}(t_{Hbr}, t^{*}_{i_l})$	Expected failure cost caused by the component that are not maintained (in subsystem i) at t_{Hbr} from the time t_{Hbr} to its individual optimum maintenance time $t^{*}_{i_l}$.
l	Index l always refers to components that are not included for maintenance at t_{Hbr} in this study.
h	Index h always refers to components that are included for maintenance at t_{Hbr} in this study
$C_{cr}\,(t_{Hbr})$	Total maintenance cost of the critical components that are scheduled at a harbor (at t_{Hbr})
C_{cr}	Total cost of critical components for maintenance planning with three predictable maintenance opportunities
$C_{KooN}(t_{Hbr})$	Total maintenance cost of KooN system that are scheduled at t_{Hbr}
C_{KooN}	Total cost of KooN systems for maintenance planning with three predictable maintenance opportunities
C_{Total}	Total maintenance cost for the studied system
$D_{t_{Hbr}}$	Total opportunity duration at a harbor (at t_{Hbr})

1. Introduction

In the future, it is expected that autonomous marine systems (AMS), such as Marine Autonomous Surface Ships (MASS) and Autonomous Underwater Vehicles (AUV) will improve cargo and personnel transportation, ocean monitoring, and subsea production and intervention [1-3]. One of the most critical issues for the safe operation of these AMS is maintaining their reliability during the operation [3-6], which requires proper and timely maintenance plans for all components.

Onboard maintenance is an essential part of the maintenance activities of conventional ships. It includes regular or routine checks and services that can be carried out by crews every day without disturbing the operations [7]. Well-trained and experienced shipboard personnel are therefore essential to ensure the system's operational availability. For autonomous systems, however, few or even no crew will be involved during the operation [3, 4]. Although certain failures can be repaired remotely through software updates or remotely controlled maintenance robots, there will certainly be situations where an experienced human team and relevant maintenance resources are indispensable. Therefore, most of the maintenance work needs to be carried out in harbors for an AMS, which lead to several new challenges.

A blackout onboard an autonomous ship, for example, may lead to loss of propulsion, which means that if the fault cannot be resolved remotely, a towing vessel and/or a maintenance crew needs to be sent out for recovery to fix the problem. These measures are usually costly. Besides, due to the lack of frequent inspection and maintenance on board, only discrete and limited maintenance windows can be utilized in the harbor, and these opportunities are usually irregular. To solve these challenges, several characteristics of the AMS should be considered:

1) High consequence of AMS shutdown, i.e., the measures to recover the system from shutdown are usually costly. For critical components a failure will lead to a system shutdown directly. The failure of non-critical components in the system may not lead to the system shutdown directly, but their potential to cause a system shutdown should be considered in the maintenance plan.
2) Limited and irregular maintenance opportunities, which means that a maintenance policy should determine the optimum maintenance harbor. The possible change on the component/subsystem until each opportunity (in the future) needs to be explicitly described in the maintenance model to determine whether and which opportunity should be used. The potential changes include potential preventive maintenance operations in earlier opportunities and corrective maintenance for failed non-critical components from onboard repairman during the voyage between opportunities.
3) Dependencies among components, such as economic dependence, structural dependence, or stochastic dependence [8-11]. For multiple components with economic dependence, grouping maintenance actions of multiple components simultaneously can reduce overall maintenance costs [12-14]. For the system with high shutdown consequence, different failure mechanism, e.g., failure caused by load-sharing between components, and different system structures, e.g., k-out-of-n (KooN) structure, should be considered to accurately simulate the system shutdown. In addition, when the maintenance opportunities are limited and irregular, the degree of these dependencies between components may vary due to potential maintenance operations in each opportunity or during the voyage. These dynamic changes need to be captured when planning maintenance.

Maintenance planning for multi-component systems has been extensively studied in the last few decades. Dekker and colleagues proposed several maintenance grouping methods for multi-component systems with economic dependency [12, 15-19]. To enable the grouping of activities and formulate a global cost function, penalty functions are proposed to describe the costs of changing the execution time of each individual component. In addition, for the grouping maintenance of a system with n components, there would be $2^n - 1$ possible groups. If the component number is large, it will cause extremely high computational costs during planning. Wildeman et al. proposed several reduction theorems to simplify and solve the problem [12]. Do and colleagues conducted a series of studies with the grouping maintenance method considering constraints, such as limited maintenance teams, availability constraints, and time-limited opportunities [20-22]. Considering two new challenges, i.e., geographical dependence and maintenance routing scheduling, Nguyen et al. proposed a dynamic maintenance planning for geographically dispersed production system [23].

In [24], a dynamic grouping method for the maintenance planning of a multi-component system is proposed, and a railway system is analyzed. Instead of using the penalty function to calculate the saved money, the method explicitly describes the total cost of the maintenance plan, providing a decision-maker with a clearer view of the maintenance cost. This method has also been applied to other systems, such as wind turbines and offshore riser systems, considering various characteristics of the system for maintenance planning [25, 26]. Extending the conventional rolling horizon approach, Wu et al. proposed a novel dynamic maintenance strategy based on the actual maintenance history and health information [27]. While the above-mentioned studies assume that the maintenance plan is based on the age of components, some studies present a grouping method for condition-based maintenance [8, 28-30]. Assuming that reliability characteristics of each component can be updated when a degradation measure is available, and the dynamic maintenance plan is determined based on the degradation states of the system.

Some studies consider other dependencies together with economic dependence [11, 21, 31-33]; however, including more than one dependency among components can be difficult. In the work by Vijayan and Chaturvedi, Bayesian Networks (BNs) are used to simulate the stochastic dependency among components. The components with high dependency are grouped together and maintained at the same time [31]. Do et al. propose a condition-based maintenance model for a two-component system considering both stochastic and economic dependencies [28]. The degradation rate of each component depends not only on its own state but also on the state of the other components. Considering different system structures, Vu et al. proposed an opportunistic maintenance model with flexible decision rules [34]. Various types of maintenance opportunities are considered for planning. The work by Fan et al. also takes the stochastic dependency into consideration of the group maintenance optimization [29]. Horenbeek and Pintelon point out the possible way to include several dependence among components in the study [32], but further studies might need to be conducted. The system structure is taken into account in the study by Vu et al. [21], and the work relates the criticality of the component to the economic dependence for maintenance planning. Liang and Parlikad presented a predictive group maintenance model for multi-system multi-components networks [35], where the maintenance plan can be improved by sharing set-up cost through at the system-level and grouping downtime at the network-level. The deterioration of the components is modeled as a continuous-time multi-state stochastic process, which considers different types of dependences at the system-level and network-level.

The aforementioned studies have been conducted in the area of maintenance planning, and the existing methods can be used to solve part of the challenges in AMS maintenance that described previously. However, due to the existence of the limited and irregular maintenance opportunities and the necessity to explicitly describe the potential changes in maintenance strategies and systems states in each opportunity and the dependence between component, e.g., caused by load-sharing or onboard repairman, these approaches cannot be directly applied for the maintenance grouping of AMS. The objective of this paper is therefore to consider the aforementioned special maintenance needs of the AMS and propose a feasible grouping strategy for maintenance planning. More specifically, the following contributions are achieved: 1) an applicable group maintenance strategy for AMS is developed by combining a grouping method and a Markov model, considering economic and stochastic dependency among components; 2) a multiphase Markov model is proposed to deal with the potential changes in the maintenance strategies and system states in the context of limited and irregular maintenance opportunities; 3) a long-time perspective is included, which means that the proposed grouping heuristic provides a better maintenance plan in the scenarios with limited and irregular maintenance opportunities, compared to the “short-sighted” methods in previous studies; 4) different types of maintenance strategies for components within the context of AMS in the maintenance planning are considered, including the onboard maintenance by crew.

The paper is organized as follows: Section 2 presents the maintenance assumptions and costs considered in this study. Section 3 proposes the cost functions used for maintenance optimization. The grouping maintenance for AMS and heuristics are then described in Section 4. Section 5 uses the cooling system as a case study to demonstrate how the proposed method is applied. Various factors that may influence the planning results and the scenarios with different operating conditions are tested in this section. Finally, the conclusions drawn from the current research are presented in Section 6.

2. Problem formulation

2.1. General assumptions

Maintenance jobs are usually scheduled at a fixed time interval, according to calendar or operation time. These time intervals are typically determined based on vendor recommendations, requirements in regulations or related to insurance, expert judgments, and historical data. However, operation of AMS means that the maintenance plan needs to be dynamic, i.e.:

- Since maintenance opportunities for AMS are limited and irregular, it may not be possible to perform maintenance exactly at the most feasible time. In addition, whether there is a maintenance opportunity may only be known when the time is approaching if the maintenance opportunities are not fixed. Therefore, opportunities used should be considered and determined dynamically.
- Taking into account the dependencies between components, the maintenance plan might need to be changed due to the failure of some components, as it may cause other components to operate under different operating conditions subsequently.
- The emergence of unexpected maintenance opportunities brings more options to operators, which may lead to changes in maintenance plans.

Therefore, a maintenance model for AMS should be able to capture the dynamic nature of the AMS maintenance and improve the decision-making.

Consider an AMS consisting of N subsystems, which are serial connected, as shown using the reliability block diagram (RBD) in Fig. 1. Component $i_j$represents the component j in subsystem i. The current study considers two types of subsystems: subsystems comprised of only one critical component and KooN systems with n identical components. For example, in Fig. 1 subsystems 2 and 4 are KooN systems. It is assumed that all components have Weibull distributed failure times, and then the failure rate of component i_j, denoted as $z_{i_j}(t)$, can be described as Equation (1).

$$z_{i_j}(t) = \alpha_i \left(\Gamma\left(1 + \frac{1}{\alpha_i}\right) / \mathrm{MTTF}_i \right)^{\alpha_i} t^{\alpha_i - 1} \tag{1}$$

where t is the operational time of components, excluding the downtime caused by maintenance or other actions; $\alpha_i (> 0)$ is the shape parameter of Weibull distribution of any component in subsystem i, and MTTF_i is the mean time to failure (MTTF) of any component in subsystem i, given the assumption that every component in subsystem i are identical. $\Gamma(\cdot)$ denotes the gamma function.

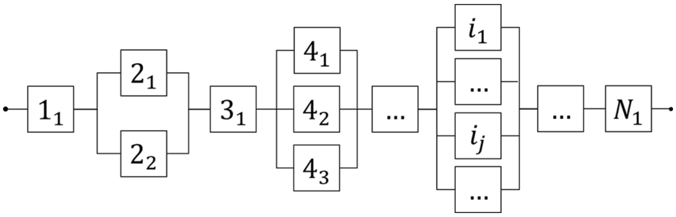

Fig. 1 Example of the system configuration illustrated by a reliability block diagram

To avoid functional failure, each component is preventively maintained after a specific operational period. Once a component fails, corrective maintenance is required. The strategy of the corrective maintenance may be different, depending on the criticality of the failed component:

- If the component is critical, a corrective maintenance should be performed immediately due to system shutdown.
- If the component is not critical, i.e., components in KooN system, maintenance can be delayed and grouped with other components until the next maintenance in the harbor, or maintenance crew can be brought onboard when the ship arrives in the next harbor and make repairs during the voyage. The choice depends on the availability of the harbor and crew.

It is assumed that the maintained component is brought back to an as good as new (AGAN) condition. The limited maintenance duration in each maintenance opportunity may leave constraints on maintenance operations, which are considered in the proposed method. In this study, it is assumed that only a single repairman is considered at each maintenance opportunity, which means that only one maintenance activity can be performed at a time. Therefore, if multiple maintenance activities are performed together, they are performed in sequence and the total maintenance duration is equal to the sum of the durations of these maintenance activities. Other possible challenges and constraints in maintenance planning of AMS, such as availability constraint, limited maintenance teams, multiple repairmen, are not focus of the study and thus not further discussed in the current study. Previous literature can be referred if interested [20].

2.2. Maintenance costs

The aim of the maintenance optimization model is to construct an optimized group structure to reduce the maintenance cost. Generally, the costs that need to be considered to determine the maintenance plan includes:

- Set-up cost: the set-up costs, denoted as S, are the costs required for preparing the maintenance actions, e.g., preparation tasks by maintenance crews, for maintenance tools, and logistics costs. In a multi-component system, set-up costs can be saved by performing maintenance actions on a group of components simultaneously [8, 12, 20].
- Planned maintenance cost: C_i^P, is a specific maintenance cost of any component in subsystem i, depending on the component's characteristics, typically the cost of replacing one unit periodically. It is assumed that the planned downtime cost caused by planned maintenance is included in C_i^P.
- Unplanned maintenance cost: unplanned costs need to be paid when a component fails. These costs, denoted as $C_{i_j}^U$, can be expressed as

$$C_{i_j}^U = C_i^{sc} + Pr\left(SSD \mid CF_{i_j}\right) \times C_{i_j,sys}^u \tag{2}$$

where C_i^{sc} is a specific failure-repair cost of any component in subsystem i, depending on its characteristics.

$Pr\left(SSD \mid CF_{i_j}\right)$ represents the probability that component i_j failure (CF_{i_j}) leads to a system shutdown (SSD).

$C_{i_j,sys}^u$ represents the system shutdown costs caused by the failure of component i_j. It usually includes two parts: system recovery costs, C_{sys}^r, and downtime costs, $C_{i_j,sys}^d$, caused by the failure of component i_j. As far as the AMS is concerned, once the system fails, a towing vessel needs to be sent out to recover it, or a maintenance team needs to be sent out to the sea to fix the problem. The cost that paid to recover the AMS, denoted as C_{sys}^r, is usually very high. In addition, an unplanned downtime cost is paid when the system is stopped to perform corrective maintenance actions. This cost is usually caused by the high cost of production loss or offhire, which depends on the downtime cost rate, denoted as C_{sys}^{DT}, and the delay time initiated by component i_j, denoted as DT_{i_j}. Hence, $C_{i_j,sys}^{u}$ can be expressed by

$$C_{i_j,sys}^{u} = C_{sys}^{r} + C_{i_j,sys}^{d} = C_{sys}^{r} + \mathrm{DT}_{i_j} \times C_{sys}^{\mathrm{DT}} \tag{3}$$

This cost model demonstrates that the unplanned maintenance cost not only depends on the specific failure-repair cost of the component, but also on the possibility of the component failure causing the system to shut down.

2.3. Maintenance grouping and problem formulation

Suppose that an autonomous ship is sailing at sea, and preventive/corrective maintenance might be required. As shown in Fig. 2, assuming that the current time is t_0, the autonomous ship is currently in harbor (Harbor A at t_A) and has a chance for maintenance. In addition, several other maintenance opportunities are available in the sailing plan in the foreseeable future, such as Harbors B and C at the time t_B and t_C, respectively. It should be noted that the timeline in Fig. 2 only demonstrates the operational time of the autonomous ship. System downtime due to maintenance or other actions are not shown in Fig. 2. For a maintenance model of a multi-component system, the aim is to construct an optimized group structure to reduce the maintenance cost. Therefore, the developed maintenance model should be able to determine: 1) whether these available opportunities should be used; and 2) if so, when is the next opportunity should be used. For a multi-component system, the maintenance plan also needs to determine; 3) how many and which components should be maintained in each opportunity.

Fig. 2 Illustration of the studied problem

3. Development of cost function for each component/subsystem

Given the general assumptions and necessary data mentioned in Section 2, Sections 3 and 4 provide the method for developing the cost functions and the heuristic for maintenance grouping. The overall framework of the proposed maintenance planning method is shown in Fig. 3. The detailed explanation of each step is as follows.

Maintenance optimization aims to determine effective maintenance plans for systems to meet requirements for safety, reliability, and availability [28]. First, the cost functions for optimization need to be formulated. Due to the different strategies of corrective maintenance, two different maintenance models are proposed for the subsystems consisting of only critical components or KooN systems.

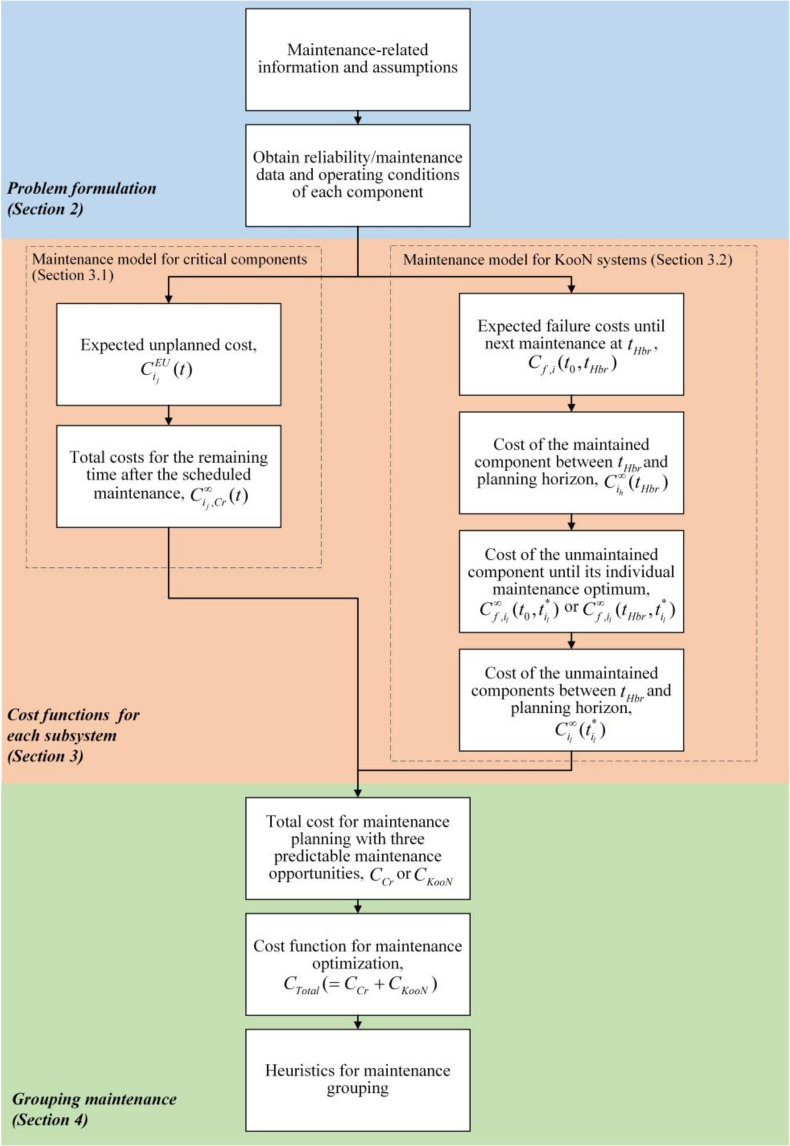

Fig. 3 Framework of the proposed maintenance planning method

3.1. Maintenance model for critical components

If component i_j is replaced at a fixed maintenance interval τ, a standard form of the maintenance optimization model for finding the optimal maintenance interval can be described by Equation (4). This equation takes into account the planned maintenance cost and the unplanned maintenance cost per unit time in time interval τ.

$$c_{i_j}(\tau) = C_i^P/\tau + \lambda_{E,i_j}(\tau) \times C_{i_j}^U \tag{4}$$

where $\lambda_{E,i_j}(\tau)$ is the effective failure rate of component i_j in time interval τ, which is the expected number of failures per unit time.

For a critical component i_j, an accumulated expected cost due to failures in a period $[0, x)$ with the last preventive maintenance activity at time 0, $M_{i_j}(x)$, can be calculated using Equation (5). This is expressed as the product of the number of unplanned maintenance (calculated by multiplying time, x, by the effective failure rate, $\lambda_{E,i_j}(x)$) and the cost of each unplanned maintenance operation, $C_{i_j}^{U}$. The system shutdown cost needs to be paid due to the criticality of the component.

$$M_{i_j}(x) = x \times \lambda_{E,i_j}(x) \times C_{i_j}^{U} = x \times \lambda_{E,i_j}(x) \times [C_i^{sc} + C_{sys}^{r} + \mathrm{MDT}_i \times C_{sys}^{DT}] \tag{5}$$

where MDT_i is the mean downtime (MDT) of any component in subsystem i

The effective failure rate of component i_j, $\lambda_{E,i_j}(x)$ can be established for different failure characteristics and maintenance strategies. Considering that all components are assumed to be Weibull distributed, a simple approximation formula of the effective failure rate is given by Equation (6) [36].

$$\lambda_{E,i_j}(\tau) = \left(\Gamma\left(1 + \frac{1}{\alpha_i}\right)/\mathrm{MTTF}_i\right)^{\alpha_i} \tau^{\alpha_i - 1} \gamma(\tau, \alpha_i, \mathrm{MTTF}_i) \tag{6}$$

where the correction term $\gamma(\tau, \alpha_i, \mathrm{MTTF}_i) = \left[1 - 0.1\alpha_i \tau^2/\mathrm{MTTF}_i{}^2 + (0.09\alpha_i - 0.2)\tau/\mathrm{MTTF}_i\right]$.

Therefore, considering the economic dependence through shared set-up cost; if component i_j is maintained together with other $k - 1$ components simultaneously, the average costs per unit time for component i_j after the maintenance, $\Phi_{i_j}(x)$, can be described by combining the planned maintenance costs and the unplanned maintenance costs, as shown in Equation (7).

$$\Phi_{i_j}(x) = [C_i^P + S/k + M_{i_j}(x)]/x \tag{7}$$

Suppose the current time is t_0, and component i_j is planned to be preventively maintained at time t. The expected unplanned cost of component i_j in the period $[t_0, t)$, $C_{i_j}^{EU}(t)$, can be calculated by Equation (8), while the expected planned cost is the summary of C_i^P and S/k.

$$C_{i_j}^{EU}(t) = M_{i_j}\left(t - t_0 + x_{i_j}\right) - M_{i_j}\left(x_{i_j}\right) \tag{8}$$

where x_{i_j} is the current age of component i_j at the time t_0 since the last preventive maintenance.

After the maintenance, the component is assumed AGAN. Let $\Phi_{i_j}^*$ be the minimum average costs per unit time when critical component i_j is optimized individually. Then, for the remaining time of the planning horizon, the total costs can be calculated as the product of the remaining time length and the minimum average costs per unit time, as shown in Equation (9). This is based on the assumption that component i_j can be maintained at a “perfect match” with $k - 1$ activities in the rest of the period. $x_{i_j}^*$ will be the optimum maintenance interval of component i_j.

$$C_{i_j,Cr}^{\infty}(t) = (T - t) \times \Phi_{i_j}^* \tag{9}$$

where $\Phi_{i_j}^* = \Phi_{i_j}\left(x_{i_j}^*\right) = min[C_i^P + S/k + M_{i_j}(x)]/x$

For the subsystem that comprised of only one critical component, the index j is always equal to one in component i_j. Therefore, the total maintenance cost of a critical component (in subsystem i) with the next planned maintenance time at t, can be denoted as $C_{Cr,i_1}(t)$.It can be described by Equation (10).

$$\begin{aligned} C_{Cr,i_1}(t) &= C_i^P + S/k + C_{i_1}^{EU}(t) + C_{i_1,Cr}^{\infty}(t) \\ &= C_i^P + S/k + M_{i_1}\left(t - t_0 + x_{i_1}\right) - M_{i_1}\left(x_{i_1}\right) + (T - t) \times \Phi_{i_1}^* \end{aligned} \tag{10}$$

3.2. Maintenance model for KooN systems using a Markov model considering load-sharing

In this study, the structural dependence between components and the load-sharing between components are considered. Since the failure of a component in a KooN system does not lead to the system shutdown immediately, the strategy of corrective maintenance is different from that of other critical components. Thus, a Markov model considering load-sharing is derived. This means that when all components are functioning, they share a common load and operate at a lower rate. If one component fails, however, corrective maintenance may not be required immediately during the ship's voyage. Then the remaining component(s) has to carry the whole load until the failed component is maintained, and it can be assumed that its failure rate increases as the load increases.

3.2.1. Expected failure costs until next maintenance

Whether the studied system will be functioning until the next maintenance to avoid the system shutdown is of interest to operators and maintenance planners. Therefore, the expected failure cost of the studied KooN system until the next maintenance opportunity needs to be locally considered.

If maintenance is scheduled at the current harbor, which is Harbor A in Fig. 2, no failure cost incurs, and only set-up cost and the corresponding preventive maintenance cost is required at t_0.

If the maintenance is scheduled at the next harbor, i.e., Harbor B (t_B), the dynamic condition of the studied load-sharing system between the time t_0 and t_B can be modeled using the Markov model.

For illustration, a 1oo2 system is analyzed as an example. During a voyage, it may experience four possible states, as shown in Table 1. Fig. 4 illustrates the representation of the Markov model for the studied system and the possible transitions between the states described in Table 1. It is assumed that the system starts with two functioning components, and the initial state of the Markov model is State 3. The transition rates λ_{i_1} and λ_{i_2} can be determined by the average failure rates of the component 1 and 2 in the studied 1oo2 system i during the current voyage, calculated using Equation (11). Once a component fails, corrective maintenance will not be performed immediately in accordance with the maintenance strategy; that is, there is no transition from State 1 to State 3 or from State 2 to State 3. Meanwhile, the remaining functioning component will carry a higher load and thus experience a higher failure rate during the remaining journey, which is represented as $\lambda_{i_1,high}$ or $\lambda_{i_2,high}$ in Fig. 4. Once both components fail (State 0), the whole system shuts down immediately, and system recovery and corrective maintenance are required. The transition rate from State 0 to State 3 is the repair rate of any component in the studied 1oo2 system i, denoted as μ_i.

Table 1 Possible states of a load-sharing parallel system with two identical components

State	Component 1	Component 2
3	Functioning	Functioning
2	Failed	Functioning
1	Functioning	Failed
0	Failed	Failed

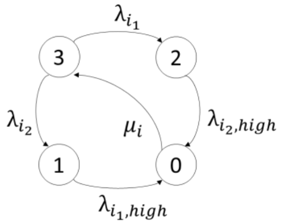

Fig. 4 State transition diagram of a load-sharing parallel system with two identical components

$$\lambda_{i_j} = \frac{1}{x_{i_j,t_B} - x_{i_j,t_0}} \times \int_{x_{i_j,t_0}}^{x_{i_j,t_B}} z_{i_j}(t)dt \tag{11}$$

where $x_{i_j,t}$ is the age of component i_j in studied 1oo2 system at time t. $z_{i_j}(t)$ is the failure rate of component i_j in studied 1oo2 system at time t, which can be calculated based on Equation (1).

Given the constructed Markov model and the assumptions mentioned above, the dynamic changes of the system between the time t_0 and t_B can be calculated using the time-dependent solution of a Markov process. Let $\boldsymbol{A}$ be the transition rate matrix of the Markov process and $\boldsymbol{P}(t)$ be the time-dependent probability vector for the various states defined in $\boldsymbol{A}$. According to the Markov differential equations, Equation (12) can be repeatedly used to obtain the approximate time-dependent solution of a Markov process [37].

$$\boldsymbol{P}(t + \Delta t) = \boldsymbol{P}(t)e^{\boldsymbol{A}\Delta t} \approx \boldsymbol{P}(t)[\boldsymbol{A}\Delta t + \boldsymbol{I}] \tag{12}$$

where Δt is a small time interval and $\boldsymbol{I}$ is the identity matrix.

In general, the expected failure costs during this period include expected downtime cost, recovery costs caused by a system shutdown and corresponding specific failure-repair costs. In the current Markov model, the system downtime (of the autonomous ship) is the total time that the studied 1oo2 system is in State 0. The expected downtime caused by 1oo2 system i during the period from t_0 and t_B, represented by $\mathrm{DT}_i(t_0, t_B)$, can be obtained by summing up the multiplication of the time interval, Δt, and the probability that the system is in State 0 during each interval from t_0 to t_B. A general form to calculate this expected downtime between the time τ_1 and τ_2 is described in Equation (13).

$$\mathrm{DT}_i(\tau_1, \tau_2) = \sum_{q=0}^{(\tau_2-\tau_1)/\Delta t} [\Delta t \times P_{i,0}(\tau_1 + q\Delta t)] \tag{13}$$

where $P_{i,m}(t)$ is the time-dependent value of the probability that subsystem i is in State m at time t.

In addition, each time that the 1oo2 system i visits State 0, the system recovery cost and specific failure-repair costs of the components incur. The expected number of times that the 1oo2 system i visits State 0 during the period from t_0 and t_B, denoted as $\nu_{i,0}(t_0, t_B)$, can be calculated based on Equation (14), which is a general form to calculate the expected number of times that subsystem i visits State 0 between time τ_1 and τ_2. The equation is obtained by summing up the multiplication of the time interval, Δt, and the frequency of transitions from States 1 or 2 to State 0 in this interval.

$$\nu_{i,0}(\tau_1, \tau_2) = \sum_{q=0}^{(\tau_2-\tau_1)/\Delta t} \{[P_{i,1}(\tau_1 + q\Delta t) \times \lambda_{i_1,high} + P_{i,2}(\tau_1 + q\Delta t) \times \lambda_{i_2,high}] \times \Delta t \tag{14}$$

Therefore, the expected failure cost caused by the studied 1oo2 system i between the time t_0 and t_B, represented as $C_{f,i}(t_0, t_B)$, can be calculated using Equation (15).

$$C_{f,i}(t_0, t_B) = \mathrm{DT}_i(t_0, t_B) \times C_{sys}^{\mathrm{DT}} + \nu_{i,0}(t_0, t_B) \times (C_{sys}^{r} + 2 \times C_i^{sc}) \tag{15}$$

A possible alternative is that maintenance is scheduled in Harbor C (in Fig. 2). In this case, a potential maintenance opportunity might be accessible when the ship arrives in Harbor B. This potential opportunity might reduce the risk of component and system failure when the ship is sailing from Harbor A to C. With different situations of the system at Harbor B, different maintenance strategies may be applied in the second part of the voyage. This means that in the simulation of Markov model, system state may change immediately at Harbor B with potential maintenance activities. For example, the system state may need to be reinitialized since some components are maintained to AGAN, or the transition rates between states need to change during the voyage from Harbor B to C due to changed failure rate or repair rate. Then the Markov model above should be adapted to consider the possible changes at Harbor B.

Therefore, a multiphase Markov model is thus proposed to handle such discrete maintenance opportunities and potential different maintenance strategies. A multiphase Markov process is "a Markov process where the parameters and the state of the system can be changed at predefined points in time", and the phases indicate the time periods between the changes [37]. This multiphase Markov process may occur due to the change of the transition rates or the change of the initial state, which can be used to describe the possible phase change at Harbor B as mentioned previously.

During the voyage from t_0 to t_B, corrective maintenance is only required if the system shuts down. This period can be described using the Markov model shown in Fig. 4. When the ship arrives in Harbor B at t_B, subsystem i may be in three different states (State 1, State 2, and State 3) with different probabilities. It is noted that the possibility that subsystem i is in State 0 is ignored, assuming that the ship cannot enter the harbor and shut down precisely at the time t_B. Even if the ship shuts down just before the harbor, system shutdown costs will incur, which has been considered in the first phase of the model.

Given the different probabilities in the three states at the time t_B, different strategies might be required at Harbor B. It is assumed that Harbor B can provide an opportunity to bring one repairman on board to perform the corrective maintenance on a failed component without shutting down the ship (offhire). The decision whether to bring one repairman onboard depends on the system state. If both components are functioning (State 3), the ship can continue the voyage as planned, and the second phase of the Markov model (from t_B to t_C) remains unchanged from the first phase of the model (from t_0 to t_B).

If one component in subsystem i has failed (either State 1 or 2), bringing a repairman onboard should be considered at Harbor B. Thus, the transitions from State 1 or State 2 to State 3 are possible, with a transition rate of μ_i. When Harbor C is planned to be used, the option of stopping the voyage and waiting for the failed non-critical component (in KooN system) to be repaired at Harbor B is ignored due to the incurred high downtime cost and potential logistic costs. The two-phase Markov model is demonstrated in Fig. 5, and $\lambda_{i_j}{}'$ and $\lambda_{i_j,high}{}'$ stand for the transition rates during the second phase, which is from t_B to t_C.

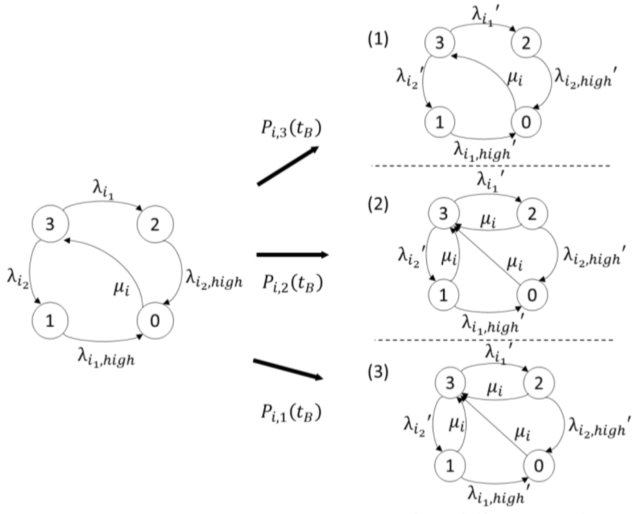

Fig. 5 Demonstration of the two-phase Markov model

Therefore, the expected failure costs during the period from t_0 to t_C include two parts: the expected failure costs from t_0 to t_B, $C_{f,i}(t_0, t_B)$, as described in Equation (14), and the expected failure costs from t_B to t_C, $C_{f,i}(t_B, t_C)$.

The expected system downtime from t_B to t_C, $\mathrm{DT}_i(t_B,t_C)$, depends on the condition of the subsystem i at t_B. It can be calculated using the law of total probability, as described in Equation (16).

$$\mathrm{DT}_i(t_B,t_C) = P_{i,3}(t_B) \times \mathrm{DT}_{i,3}(t_B,t_C) + P_{i,2}(t_B) \times \mathrm{DT}_{i,2}(t_B,t_C) + P_{i,1}(t_B) \times \mathrm{DT}_{i,1}(t_B,t_C) \quad (16)$$

where $\mathrm{DT}_{i,m}(t_B,t_C)$ is the expected downtime that the system may experience during the period from t_B to t_C, given that subsystem i is in State m in the Harbor B at the time t_B. It can be calculated based on Equation (13).

Similarly, the expected number of times that visits State 0 between time t_B and t_C, $\nu_{i,0}(t_B,t_C)$, can be calculated using Equation (17).

$$\nu_{i,0}(t_B,t_C) = P_{i,3}(t_B) \times \nu_{i,0,3}(t_B,t_C) + P_{i,2}(t_B) \times \nu_{i,0,2}(t_B,t_C) + P_{i,1}(t_B) \times \nu_{i,0,1}(t_B,t_C) \quad (17)$$

where $\nu_{i,0,m}(t_B,t_C)$ is the expected number of times that subsystem i visits State 0 during the period from t_B to t_C, given that subsystem i is in State m in the Harbor B at the time t_B. It can be calculated based on Equation (14).

In the second phase, due to the possible existence of a repairman, the corrective maintenance might be performed on board. If there is repairman on board, the corrective maintenance cost of the failed component, C_i^{sc}, needs to pay if any failed component is repaired during the voyage. In the Markov model, the cost needs to be paid each time that subsystem i transfer from either State 1 or State 2 to State 3 during the period from t_B to t_C. The corresponding number of transfers is denoted as $\nu_{i,12\to3}$, and it can be calculated using Equation (18).

$$\nu_{i,12\to3}(t_B,t_C) = P_{i,2}(t_B) \times \nu_{i,12\to3,2}(t_B,t_C) + P_{i,1}(t_B) \times \nu_{i,12\to3,1}(t_B,t_C) \quad (18)$$

where $\nu_{i,12\to3,m}(t_B,t_C)$ is the expected number of times that subsystem i transfers from either State 1 or State 2 to State 3 during the period from t_B to t_C, given that the 1oo2 system i is in State m in Harbor B at time t_B. It can be calculated using Equation (19).

$$\nu_{i,12\to3,m}(\tau_1,\tau_2) = \sum_{q=0}^{(\tau_2-\tau_1)/\Delta t}\{[P_{i,1}(\tau_1+q\Delta t) \times \mu_i + P_{i,2}(\tau_1+q\Delta t) \times \mu_i] \times \Delta t\} \quad (19)$$

It should be noted that during the calculation of $\mathrm{DT}_{i,m}(t_B,t_C)$, $\nu_{i,0,m}(t_B,t_C)$, and $\nu_{i,12\to3,m}(t_B,t_C)$ in the second phase of the model, the time-dependent probability vector needs to be initialized, and it should reflect the corresponding assumed scenario. For example, let $\boldsymbol{P}_i(t_B) = [0,0,1,0]$ when calculating the value of $\mathrm{DT}_{i,2}(t_B,t_C)$, $\nu_{i,0,2}(t_B,t_C)$, and $\nu_{i,12\to3,2}(t_B,t_C)$. The expected failure costs of the studied 1oo2 system i during the period from t_0 to t_C, $C_{f,i}(t_0,t_C)$, can be calculated as:

$$\begin{aligned}C_{f,i}(t_0,t_C) &= C_{f,i}(t_0,t_B) + C_{f,i}(t_B,t_C)\\ &= \mathrm{DT}_i(t_0,t_B) \times C_{sys}^{\mathrm{DT}} + \nu_{i,0}(t_0,t_B) \times \left(C_{sys}^{r} + 2 \times C_i^{sc}\right) + \mathrm{DT}_i(t_B,t_C) \times C_{sys}^{\mathrm{DT}}\\ &\quad + \nu_{i,0}(t_B,t_C) \times \left(C_{sys}^{r} + 2 \times C_i^{sc}\right) + \nu_{i,12t\to3}(t_B,t_C) \times C_i^{sc}\\ &= \mathrm{DT}_i(t_0,t_C) \times C_{sys}^{\mathrm{DT}} + \nu_{i,0}(t_0,t_C) \times \left(C_{sys}^{r} + 2 \times C_i^{sc}\right) + \nu_{i,12\to3}(t_B,t_C) \times C_i^{sc} \quad (20)\end{aligned}$$

In the current study, only one-phase and two-phase Markov models are shown as examples. However, if more maintenance opportunities are available in the foreseeable future, a similar method can be applied to develop multiphase Markov models to calculate the expected failure cost. In addition, the representation of the Markov model can be changed according to the various assumed maintenance strategies and operating conditions.

3.2.2. Average maintenance cost

Similar as the assumption for critical components, after the maintenance, an average maintenance cost is paid for the remaining time of the planning horizon based on the average maintenance situation. Since two components in a 1oo2 system are not maintained simultaneously every time, the average maintenance cost is required for the maintained one. Therefore, the average cost function needs to reflect the maintenance cost of each single component.

A 5-state Markov model is thus developed to calculate the maintenance cost incurred by a specific component, as shown in Fig. 6. The State 0 in the previous models is divided into State 0.1 and State 0.2 to represent the shutdown states of subsystem i that are directly caused by the failure of Component 1 and 2, respectively. The transition rates $\lambda_{i_j,ave}$ represents the failure rate used in the simulation of the average situation, and $\lambda_{i_j,high,ave}$ represents the higher failure rate caused by the load-sharing mechanism. In the average maintenance situation, the transitions from State 1 or State 2 to State 3 are possible, considering the maintenance by a repairman or in harbors. However, maintenance might not be accessed immediately during the voyage, and it can be performed at the next harbor at the earliest. This logistic delay needs to be considered in the maintenance planning. Therefore, the repair rate from State 1 or State 2 to State 3, represented as μ_i^-, can be calculated as Equation (21), assuming that an average logistics delay is half of an average sailing period cycle.

$$\mu_i^- = \frac{1}{\mathrm{MRT}_i + \text{logistics delay}} = \frac{1}{\mathrm{MRT}_i + 0.5 \times \text{typical sailing cycle}} \tag{21}$$

where MRT_i is the mean (active) repair time of any component in subsystem i.

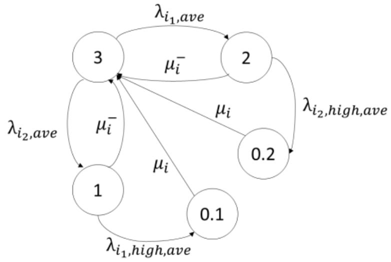

Fig. 6 Markov model used for the calculation of the average maintenance cost of a single component

Assume that both components are maintained every x hours, the failure rate $\lambda_{i_j,ave}$ can be calculated using Equation (6). Taking Component 1 in the studied 1oo2 system i for example, the preventive maintenance, C_i^P, and the set-up cost constitute the planned maintenance cost. In terms of the unplanned maintenance cost, the system recovery cost, C_{sys}^r, and corresponding corrective maintenance cost, C_i^{sc}, need to be considered in the cost function each time the failure of Component 1 causes the system shutdown directly. A system downtime cost is required, depending on the time that subsystem i spends in the system shutdown state (State 0.1). In addition, corrective maintenance costs are required every time the failed Component 1 is maintained before it causes the system to shut down.

Generally, given the constructed Markov model and assumptions mentioned above, Equation (22) can be minimized to find the individual optimum average maintenance cost, $\Phi_{i_1,ave}^*$, and individual optimum maintenance interval, $x_{i_1,ave}^*$, for Component 1.

$$\Phi_{i_1,ave}(x) = \frac{C_i^P + S/k}{x} + P_{i,0.1} \times C_{sys}^{DT} + P_{i,1} \times \lambda_{i_1,high,ave} \times (C_{sys}^r + C_i^{sc}) + P_{i,2} \times \mu_i^- \times C_i^{sc} \tag{22}$$

where $P_{i,m}$ represents the steady-state probability of State m in subsystem i.

In the current study, since the same assumptions are applied to Component 2, it is easy to conclude that $\Phi_{i_2,ave}^* = \Phi_{i_1,ave}^*$ and $x_{i_2,ave}^* = x_{i_1,ave}^*$. Let $\Phi_{i,ave}^* = \Phi_{i_1,ave}^* = \Phi_{i_2,ave}^*$ and $x_{i,ave}^* = x_{i_1,ave}^* = x_{i_2,ave}^*$ to represent the average individual optimum of either component in studied load-sharing 1oo2 system

i. Therefore, after a component in subsystem i is maintained at time t, the remaining maintenance cost can be calculated as the product of the remaining time length and the average individual optimum per unit time, using Equation (23). This is based on the assumption that component i_j can be maintained at a "perfect match" with $k-1$ activities for the remaining time period and other components in subsystem i can also be maintained at their average individual optimum for the remaining time period.

$$C^{\infty}_{i_j,KooN}(t) = (T-t) \times \Phi^{*}_{i,ave} \tag{23}$$

For a load-sharing 1oo2 system, the individual maintenance optimums of a component also depend on the conditions of the other component. However, the assumptions of the other component are based on average conditions due to the lack of more accurate information. If more accurate information of the other component can be accessed or expected, e.g., from condition monitoring, a more accurate calculation of individual optimums can be obtained.

3.2.3. Cost functions of KooN system with different maintenance strategies

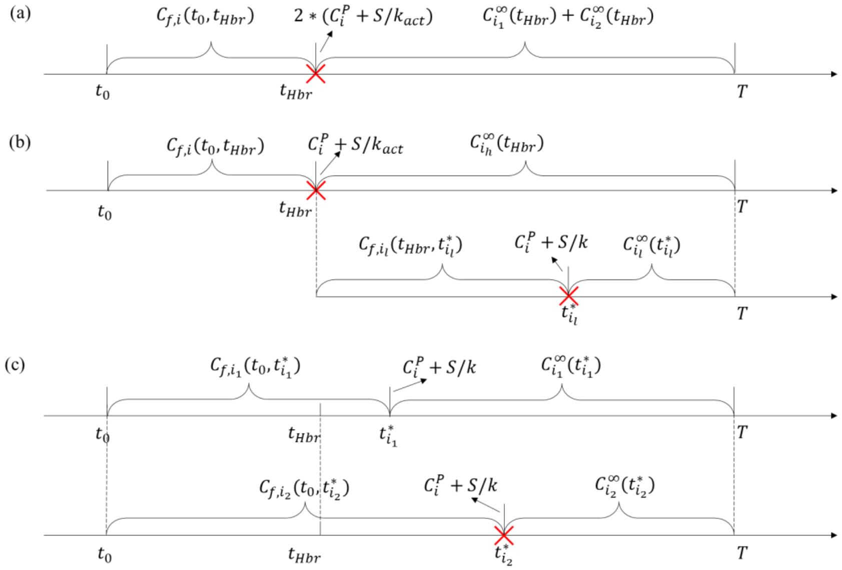

Fig. 7 Illustration of the maintenance cost of the load-sharing 1oo2 system with various maintenance strategies: (a) both components are maintained at t_{Hbr}, (b) only one component is maintained at t_{Hbr}, (c) no components will be maintained at foreseeable harbors

Fig. 7 illustrates the costs of the load-sharing 1oo2 system for different maintenance strategies.

If both components are maintained at one of the foreseeable harbors at t_{Hbr} (t_{Hbr} is equal to $t_0(t_A)$, t_B or t_C, depending on which harbor is used), the cost that needs to be paid can be illustrated in Fig. 7 (a). The costs include the expected failure cost of the 1oo2 system i until the maintenance at t_{Hbr}. In addition, the preventive maintenance cost, C_i^P, and set-up cost required at maintenance harbor, S/k_{act}, (where k_{act} is the actual number of components sharing set-up cost at maintenance harbor, depending on the actual maintenance plan) need to be paid twice for both components maintained at t_{Hbr}. For the remaining period after t_{Hbr}, the average maintenance cost will be paid for both components until the planning horizon T.

If only one component is scheduled for maintenance at t_{Hbr}, the maintenance costs that need to be considered are shown in Fig. 7 (b). Both components contribute to the expected failure cost until the maintenance time at t_{Hbr}, $C_{f,i}(t_0, t_{Hbr})$. At t_{Hbr}, one component will be maintained at the harbor, while the other component is assumed to wait until its individual optimum maintenance time. After the maintenance, an average maintenance cost is paid for each component separately.

While the cost of the component that are maintained at t_{Hbr} can be calculated using the similar method for situation in Fig. 7 (a), the method to calculate the maintenance cost for the components that are not maintained at t_{Hbr} should be formulated. The first step is to calculate $C_{f,i_l}(t_{Hbr}, t_{i_l}^*)$, which is the expected failure cost required for the component that are not maintained at t_{Hbr} from the time t_{Hbr} to its individual optimum maintenance time $t_{i_l}^*$ ($t_{i_l}^*$ is equal to $t_{i_1}^*$ or $t_{i_2}^*$, depending on which component in 1oo2 system i is not maintained at t_{Hbr}).

Suppose that Component 1 is the unmaintained component in 1oo2 system i, the Markov model shown in Fig. 6 can be used to find $t_{i_l}^*$ ($=t_{i_1}^*$ in this case). An average estimation of $t_{i_1}^*$ can be obtained using the method described in Section 3.2.1. However, since it is known that the other component (Component 2) will be maintained at t_{Hbr}, the previous assumption that the other component is based on average conditions can be relieved. Thus, the value of $t_{i_1}^*$ that calculated based on the method described in Section 3.2.1 can be updated by using the actual age of the Component 2.

The transition rate, $\lambda_{i_2,ave}$, in the period between t_{Hbr} and $t_{i_l}^*$ depends on the current age of Component 2. Given the current age, a correction factor can be applied to update this transition rate. For example, the age can be discretized into low, medium, and high, by comparing the actual age of Component 2 with the average individual optimum maintenance interval $x_{i,ave}^*$. If the current age of Component 2 is much lower than $x_{i,ave}^*$, for example less than a quarter of $x_{i,ave}^*$, a smaller value of correction factor, such as half of the $x_{i,ave}^*$, can be used to calculate the updated transition rate $\lambda_{i_2,ave}$. However, if the current age is much higher than $x_{i,ave}^*$, for example more than three quarters of $x_{i,ave}^*$, a bigger value of correction factor, such as 1.5 times of the $x_{i,ave}^*$, can be used to calculate the updated transition rate $\lambda_{i_2,ave}$. Otherwise, the transition rate $\lambda_{i_2,ave}$ can still be calculated with the average individual optimum maintenance interval $x_{i,ave}^*$. The discretization process and the choice of correction factor can be adapted according to the component's characteristics.

With a more accurate calculation of transition rate $\lambda_{i_2,ave}$, the individual optimum maintenance interval $x_{i_1}^*$ can be updated by minimizing Equation (22). The updated individual optimum maintenance interval $x_{i_1}^*$ can then be transferred to find the next individual optimum maintenance time point $t_{i_1}^*$. Similarly, $t_{i_2}^*$ can be updated if Component 2 is the unmaintained component in the 1oo2 system.

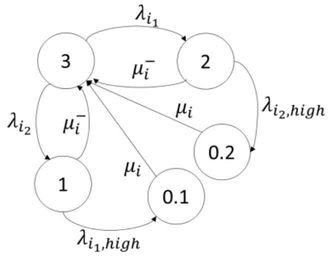

Fig. 8 Markov model for the calculation of the expected failure cost of an unmaintained component

For the calculation of the expected failure cost of the unmaintained component in subsystem i, $C_{f,i_l}(t_{Hbr}, t_{i_l}^*)$, the Markov model shown in Fig. 8 can be used. The transition rates λ_{i_1} and λ_{i_2} are calculated as the average failure rate between the t_{Hbr} and the next individual optimum maintenance time of the corresponding component. Given Component 1 is the unmaintained component, the value of $C_{f,i_l}(t_{Hbr}, t^*_{i_l})$, which is $C_{f,i_1}(t_{Hbr}, t^*_{i_1})$ in this case, can be calculated using Equation (24). A similar cost function can be developed for Component 2 if it is the unmaintained component in 1oo2 system i.

$$\begin{aligned} C_{f,i_1}(t_{Hbr}, t^*_{i_1}) = {} & \mathrm{DT}_{i_1}(t_{Hbr}, t^*_{i_1}) \times C^{DT}_{sys} \\ & + \nu_{i,0.1}(t_{Hbr}, t^*_{i_1}) \times (C^{r}_{sys} + C^{sc}_{i}) + \nu_{i,2}(t_{Hbr}, t^*_{i_1}) \times C^{sc}_{i} \end{aligned} \tag{24}$$

where $\mathrm{DT}_{i_1}(t_{Hbr}, t^*_{i_1})$ is the expected system downtime caused by Component 1 in subsystem i during the period between t_{Hbr} and $t^*_{i_1}$, which is the total time that the 1oo2 system i stays in State 0.1 in the Markov model in Fig. 8;

$\nu_{i,0.1}(t_{Hbr}, t^*_{i_1})$ is the expected number of times that the 1oo2 system i visits State 0.1 during the period between t_{Hbr} and $t^*_{i_1}$;

$\nu_{i,2}(t_{Hbr}, t^*_{i_1})$ is the expected number of times that the system visits State 2 during the period between t_{Hbr} and $t^*_{i_1}$.

If none of the foreseeable opportunities are scheduled for maintenance, both components in subsystem i are assumed to be maintained at their own next individual optimum maintenance time. After the maintenances, an average maintenance cost is paid for each component, as shown in Fig. 7 (c). It should be noted that when calculating the value of $t^*_{i_1}$ and $t^*_{i_2}$, the calculation based on the assumption of average condition that described in Section 3.2.1 can be updated using the actual age of the components at t_0.

4. Grouping maintenance

4.1. Grouping maintenance

Given the cost function of each component described in Section 3, the total cost function for maintenance grouping and planning can be developed as follows.

For critical components, the total maintenance cost of the components that are scheduled at a harbor (at t_{Hbr}) for the next maintenance, $C_{Cr}(t_{Hbr})$, is described using Equation (25).

$$\begin{aligned} C_{Cr}(t_{Hbr}) = {} & a_{t_{Hbr}} S + \textstyle\sum_{i \in G(t_{Hbr})} [C^P_i + M_{i_1}(t_{Hbr} - t_0 + x_{i_1}) \\ & - M_{i_j}(x_{i_1}) + (T - t_{Hbr}) \times \Phi^*_{i_1}] \end{aligned} \tag{25}$$

where $\mathrm{a}_{t_{Hbr}}$ is the parameter describing whether the maintenance opportunity at t_{Hbr} is utilized, and $\mathrm{a}_{t_{Hbr}} = 0$ when $G(t_{Hbr}) = \emptyset$; $\mathrm{a}_{t_{Hbr}} = 1$ when $G(t_{Hbr}) \neq \emptyset$.

The total cost for maintenance planning with three predictable maintenance opportunities at t_0, t_B, and t_C, C_{Cr}, is given by Equation (26).

$$\begin{aligned} C_{Cr} = {} & a_{t_0} S + \textstyle\sum_{i \in G(t_0)} [C^P_i + (T - t_0) \times \Phi^*_{i_1}] \\ & + a_{t_B} S + \textstyle\sum_{i \in G(t_B)} [C^P_i + M_{i_1}(t_B - t_0 + x_{i_1}) - M_{i_1}(x_{i_1}) + (T - t_B) \times \Phi^*_{i_1}] \\ & + a_{t_C} S + \textstyle\sum_{i \in G(t_C)} [C^P_i + M_{i_1}(t_C - t_0 + x_{i_1}) - M_{i_1}(x_{i_1}) + (T - t_C) \times \Phi^*_{i_1}] \\ & + \textstyle\sum_{i \notin G(t_0) \cup G(t_B) \cup G(t_C)} [C^P_i + S/k + M_{i_1}(x^*_{i_1}) - M_{i_1}(x_{i_1}) + (T - t^*_{i_1}) \times \Phi^*_{i_1}] \end{aligned} \tag{26}$$

where $G(t_0) \cap G(t_B) \cap G(t_C) = \emptyset$.

For KooN systems, taking the load-sharing 1oo2 system in Section 3 as an example, the total maintenance cost of the subsystems that are scheduled at t_{Hbr} for the next maintenance, $C_{KooN}(t_{Hbr})$, is described using Equation (27).

$$C_{KooN}(t_{Hbr}) = a_{t_{Hbr}}S + \sum_{i \in G(t_{Hbr})} \left[C_{f,i}(t_0, t_{Hbr}) + 2 \times C_i^P + C_{after\, t_{Hbr}} \right] \tag{27}$$

where $C_{after\, t_{Hbr}}$ is the cost required after the maintenance at t_{Hbr}, which depends on the maintenance strategy of the KooN systems.

$C_{after\, t_{Hbr}} = C_{i_1,KooN}^{\infty}(t_{Hbr}) + C_{i_2,KooN}^{\infty}(t_{Hbr}) = 2 \times C_{i_1,KooN}^{\infty}(t_{Hbr})$ if both components are maintained at the time t_{Hbr}, and $C_{after\, t_{Hbr}} = C_{i_h,KooN}^{\infty}(t_{Hbr}) + C_{f,i_l}\left(t_{Hbr}, t_{i_l}^*\right) + S/k + C_{i_l,KooN}^{\infty}(t_{i_l}^*)$ if only one component is maintained, where the index h represents the index of the component that maintained at t_{Hbr}.

The total cost for maintenance planning with three predictable maintenance opportunities at t_0, t_B, and t_C, C_{KooN}, is given by Equation (28).

$$\begin{aligned} C_{KooN} = {} & a_{t_0}S + \sum_{i \in G(t_0)} \left[2 \times C_i^P + C_{after\, t_0} \right] \\ & + a_{t_B}S + \sum_{i \in G(t_B)} \left[C_{f,i}(t_0, t_B) + 2 \times C_i^P + C_{after\, t_B} \right] \\ & + a_{t_C}S + \sum_{i \in G(t_C)} \left[C_{f,i}(t_0, t_C) + 2 \times C_i^P + C_{after\, t_C} \right] \\ & + \sum_{i \notin G(t_0) \cup G(t_B) \cup G(t_C)} [2 \times \left(C_i^P + S/k\right) + C_{f,i_1}\left(t_0, t_{i_1}^*\right) + C_{i_1,KooN}^{\infty}\left(t_{i_1}^*\right) \\ & + C_{f,i_2}\left(t_0, t_{i_2}^*\right) + C_{i_2,KooN}^{\infty}\left(t_{i_2}^*\right)] \end{aligned} \tag{28}$$

where $G(t_0) \cap G(t_B) \cap G(t_C) = \emptyset$.

Equations (26) and (28) can be generalized to consider more maintenance opportunities at each decision time to improve accuracy if more foreseeable harbors are available. However, it is necessary to note that considering too many foreseeable harbors at each decision point may cause a relatively high computation cost.

The total maintenance cost can be described in Equation (29). Therefore, the aim is to group the maintenance activities in the foreseeable harbors and find out the candidate group combination, $G(t_0)$, $G(t_B)$ and $G(t_C)$, to minimize the total maintenance cost C_{Total}.

$$C_{Total} = C_{Cr} + C_{KooN} \tag{29}$$

4.2. Heuristics for maintenance grouping

When grouping maintenance for components without the constraint of limited and irregular maintenance opportunities, such as many previous studies [8, 26], only the first maintenance group is considered. The next group is not considered because of the assumption that the operators can always find a reasonable time for the second group, which is rather close to the individual optimal maintenance times for those not included in the first group. However, since the maintenance opportunities are limited and irregular for AMS, if any components are not maintained in the first foreseeable harbor, they may not be maintained at their individual optimal maintenance time, thus increasing the probability of the system shutdown and the potential maintenance costs.

Therefore, more than one maintenance opportunity may need to be considered simultaneously for maintenance planning at each decision point. The concept "grouping horizon" is thus introduced and defined in this study to represent the maintenance opportunities (foreseeable harbors) considered in the maintenance planning to deal with the challenges with limited and irregular maintenance opportunities. For those components that are not scheduled for maintenance within the grouping horizon, it is assumed that they can be maintained at their individual optimal. It should be noted that because of the limited opportunities, if a component with an individual optimum time before the last foreseeable opportunity in grouping horizon is not scheduled for maintenance, it will not be maintained at its individual optimum, but in a "future harbor" after the last opportunity. The point in time for the assumed future harbor can be identified based on a typical sailing interval.

The following heuristic is therefore proposed for the AMS maintenance:

Step 1: Consider the grouping horizon with three harbors; Harbor A, Harbor B, and Harbor C, an initial estimation of the average number of components that are maintained at the same time, k, and average set-up cost for maintenance activities, S, are made. In this study, the grouping horizon with three harbors is proposed in the heuristic. The chosen grouping horizon is validated by exploring the effect of grouping horizon in maintenance planning in Section 5.4.

Step 2: For each component, the individual optimum maintenance time, $t_{i_j}^*$, is calculated. In the case of critical components, the optimum maintenance interval $x_{i_j}^*$ needs to be transferred to the global optimum time $t_{i_j}^*$. A simple transform function is $t_{i_j}^* = x_{i_j}^* + t_0 - x_{i_j}$. For components in KooN systems, the method described in Section 3.2.3 is used to identify the next optimum maintenance time point. Given the individual optimum maintenance time, $t_{i_j}^*$, for each component, the planning horizon for the maintenance optimization, T, can be chosen. The planning horizon can be initially assumed based on the current time point, t_0, and the individual optimal maintenance time, $t_{i_j}^*$. The value of T should satisfy the following property that $T \geq \max_{i=1,2,\ldots} \{t_{i_j}^*\}$.

Step 3: Let a_{t_0}, a_{t_B} an$d$ a_{t_C} be indicator variables representing whether the set-up cost is paid in each harbor. For each combination of a_{t_0}, a_{t_B} and a_{t_C}, all possible ways that can distribute the maintenance of components for the various harbors Harbor A, Harbor B, and Harbor C should be considered. The maintenance cost between t_0 and T for all possible combinations is calculated, and the combination that provides the lowest expected cost becomes the next maintenance plan. In this study, to reduce the difficulty in group formulation, the grouping method is adapted from the method by Vatn [24], considering the maintenance characteristics of AMS. An optimal global group structure can be obtained by adopting the consecutive group structure as suggested by Wildeman et al. [12], in which each group is composed of consecutive individual planned maintenance activities. Despite the consecutive group structure might not be optimal in some cases, it is proved to provide a reasonable and excellent optimization result [27]. Therefore, the "consecutive group structure" is applied in this study to reduce the candidate groups for critical components. However, the components in KooN system need to be considered individually, and all possible combinations with the candidate groups of critical components need to be analyzed. Due to the existence of the constraint of maintenance duration in each maintenance opportunity, the total duration of all operations in each group must be lower or equal to the opportunity duration $D_{t_{Hbr}}$ so that $\sum_{i \in G(t_{Hbr})}(\mathrm{MDT}_i \ or\ \mathrm{MRT}_i) \leq D_{t_{Hbr}}$.

Step 4: If $a_{t_0} = 0$ in the identified maintenance plan, the maintenance opportunity in Harbor A can be skipped, and the ship can continue sailing and follow the identified plan for future maintenance. Obviously, if more opportunities, such as Harbor D (after Harbor C), become available before the actual maintenance activity, a new maintenance optimization can be performed with Harbor B, Harbor C, and Harbor D, thus updating the maintenance plan. If $a_{t_0} = 1$, maintenance should be performed on the corresponding components in Harbor A. The maintained components will then be assumed to be AGAN after the maintenance. The next maintenance plan can then be made with new opportunities, such as Harbor B, Harbor C, and Harbor D, after the ship leave Harbor A.

5. Case study

5.1. System description

An autonomous ship is used in the following as an example to illustrate the application of the proposed maintenance planning method. Assuming that there is no onboard crew, and that only maintenance opportunities in the harbor are considered. The autonomous ship may operate for a week or several weeks for each mission, which results in limited maintenance opportunities every few weeks. In this case study, it is assumed that the ship is currently in a harbor, Harbor A, at the time point 30 000 hours, and that two foreseeable maintenance opportunities, Harbors B and C, are available in 300 hours and 700 hours, respectively, as shown in Table 2.

Table 2 Information on maintenance opportunities and the planning horizon

Parameters	Values (hrs)
Current time, $t_0(t_A)$	30 000
Time to the first maintenance harbor, t_B	30 300
Time to the second maintenance harbor, t_C	30 700
Planning horizon, T	50 000
Constraints of maintenance duration at each harbor, $[D_{t_A}, D_{t_B}, D_{t_C}]$	[200, 200, 200]

The cooling of the machinery system is one of the critical systems in a ship to ensure the safe and stable propulsion and operation. Fig. 9 shows a typical cooling system, including a fresh water central cooling system and a sea water (SW) cooling system assumed for the autonomous ship. The fresh water central cooling system is composed of two closed parts: the high-temperature freshwater (HTFW) part and the low-temperature fresh water (LTFW) part. The fresh water in the HTFW circuit circulates in the main engine where the temperature is relatively high. Meanwhile, the fresh water in the LTFW circuit is used to maintain the temperature in the HTFW circuit and other heat exchangers. The heat generated from the LTFW circuit is removed by sea water through the central cooler in the SW cooling system.

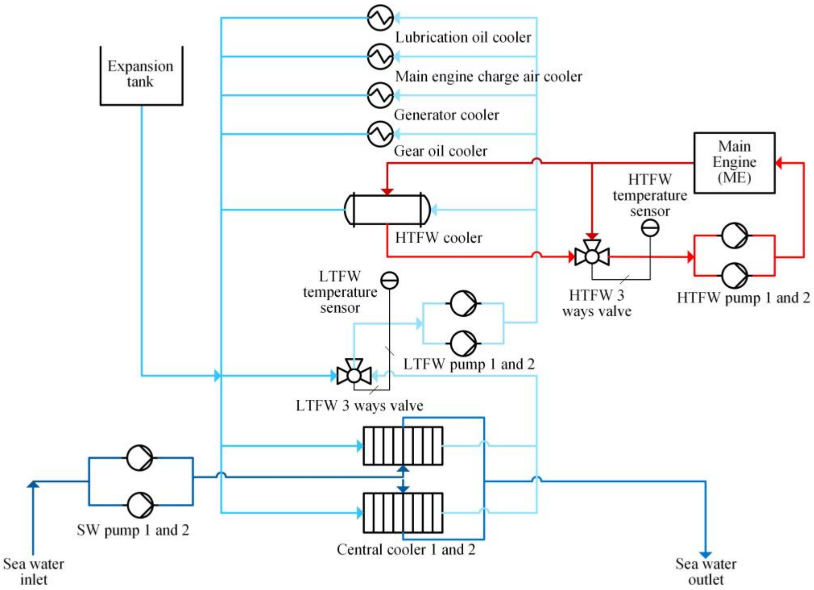

Fig. 9 Demonstration of the cooling system for an autonomous ship

In the cooling system, maintainable items such as piping, temperature sensors, 3-way valves, coolers, pumps, the expansion tank, and other major components related to cooling are selected as the main components for the maintenance planning of the cooling system. Detailed components, as well as corresponding cost information and reliability and maintainability data, are listed in Table 3. In terms of the reliability and maintainability data, the values of MTTF and MDT/ MRT of most components are obtained from OREDA [38], while the value of α, shape parameter of Weibull distribution, is assumed considering the wear-out period of each component. Also, it is assumed that subsystems, including the HTFW pump system, LTFW pump system, Central coolers, and SW pump system, are KooN systems, and components in these subsystems need to share a common load with other components in the subsystems. Other components in the cooling system are assumed to be critical components, and the failure of these components can lead to the system shutdown immediately. All components are assumed to be functioning currently with their own local age of x_{i_j}.

Table 3 Cost information and reliability and maintainability data of main components in the cooling system

Id.	Components	C_i^P (USD)*	C_i^{sc} (USD)*	MTTF_i (hrs)	α_i*	$\mathrm{MDT}_i/\mathrm{MRT}_i$ (hrs)	x_{i_j} (hrs)
1_1	HTFW piping	400	2000	2000	3	10	600
2_1	HTFW temperature sensor	150	800	40000	2.5	5	1500
3_1	HTFW 3 ways valve	500	3000	20000	3.5	30	500
4_1	HTFW cooler	2000	10000	20000	3.5	35	2000
5_1	Expansion tank	500	3000	8000	3	5	1500
6_1	LTFW piping	400	2000	2000	3	10	450
7_1	LTFW temperature sensor	150	800	40000	2.5	5	2500
8_1	LTFW 3 ways valve	500	3000	20000	3.5	30	1000
9_1	Lubrication oil cooler	1500	8000	2500	3.5	30	250
10_1	Main engine charge air cooler	1800	10000	1800	3.5	0	400
11_1	Generator cooler	1000	5000	1800	3.5	0	100
12_1	Gear oil cooler	1500	8000	2500	3.5	30	100
13_1	SW piping	400	2000	2000	3	10	100
14_1	HTFW pump 1 (engine driven)	2000	6000	40000	3.5	100	25000
14_2	HTFW pump 2 (engine driven)	2000	6000	40000	3.5	100	20000
15_1	LTFW pump 1 (electric driven)	2000	6000	12500	3.5	4	2000
15_2	LTFW pump 2 (electric driven)	2000	6000	12500	3.5	4	4000
16_1	Central cooler 1	3000	8000	7300	3.5	70	500
16_2	Central cooler 2	3000	8000	7300	3.5	70	500
17_1	SW pump 1 (electric driven)	2000	6000	12500	3.5	4	3000
17_2	SW pump 2 (electric driven)	2000	6000	12500	3.5	4	3000

Note: the values marked with * are the assumed reliability and maintainability data

5.2. Maintenance grouping

Table 4 lists the parameters used for the case study. Taking into account the cost of the maintenance team, disassembling or re-assembling a machine, etc., the set-up cost is assumed as 3 000 USD and is the same for maintenance in each harbor; the system failure cost is assumed as 5 000 USD considering the cost paid to rent a towing vessel to recover the shutdown ship or a helicopter to send out the maintenance team; the downtime rate is assumed based on the charter rate of a 2 500 TEU (twenty-foot equivalent units) container ship.

Table 4 Parameters used in the maintenance planning

Parameters	Values
Set-up costs, S	3000 USD
System recovery cost, C_{sys}^r	5000 USD
Downtime (offhire) rate, C_{sys}^{DT}	500 USD/hr
Average number of components sharing the set-up costs, k	6

According to equations described in Section 3, the next individual optimum maintenance time for each component is calculated. Detailed information of calculated $t_{i_j}^*$ is listed in Appendix A. The planning horizon for the maintenance planning, T, is then determined according to the global individual optimum time, t_{ij}^*, as shown in Table 2. In this study, the establishment of potential candidate groups and the optimization of the maintenance planning are simulated and calculated using MATLAB, following the steps and equations demonstrated in Sections 3 and 4.

According to the simulation results, the maintenance plan shows that out of 21 components (in 17 subsystems), a total of 10 components need to be considered in one of the foreseeable maintenance opportunities, while other components can skip these opportunities from the economic perspective and wait for the future opportunities. The detailed information of the plan is shown in Table 5. According to the plan, all components considered for maintenance should ignore the maintenance opportunities in Harbor A and Harbor B and use Harbor C for maintenance. The total maintenance cost until the end of the planning horizon is calculated as 4.670×10^5 USD.

Table 5 Maintenance plan according to the simulation results

Id.	Component	Maintenance plan with the proposed planning method	Maintenance plan without considering economic dependence
1_1	HTFW piping	PM: C	PM: A
2_1	HTFW temperature sensor	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait
4_1	HTFW cooler	Wait	Wait
5_1	Expansion tank	PM: C	Wait
6_1	LTFW piping	PM: C	PM: B
7_1	LTFW temperature sensor	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait
9_1	Lubrication oil cooler	PM: C	PM: C
10_1	Main engine charge air cooler	PM: C	PM: B
11_1	Generator cooler	PM: C	PM: C
12_1	Gear oil cooler	PM: C	PM: C
13_1	SW piping	PM: C	PM: C
14_1	HTFW pump 1 (engine driven)	PM: C	PM: C
14_2	HTFW pump 2 (engine driven)	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait
16_1	Central cooler 1	Wait	Wait
16_2	Central cooler 2	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: C	PM: C
17_2	SW pump 2 (electric driven)	Wait	Wait
Total components need to be maintained		10	8
Total maintenance cost (USD)		466969	471981

Note: PM: C represents the preventive maintenance in Harbor C. Wait reprents the components should skip the foreseeable opportunities and wait for future opportunities

Maintenance planners and operators are usually interested in the total cost saving of introducing a new maintenance planning method. This can be calculated by comparing the total costs with and without the proposed maintenance planning method. Without considering the maintenance grouping method, each component is optimized individually, regardless of the set-up cost sharing with other components. Given the foreseeable opportunities, each component is assumed to be maintained in its own optimum opportunity. However, since some components may still be scheduled in the same harbor according to their own individual optimization process, the maintenance of those components only needs to pay the set-up cost once. The maintenance plan without applying the proposed method is shown in Table 5. According to the simulation results, the total maintenance cost without applying the proposed method is 4.720×10^5. Therefore, in this case, the total cost saving by applying the proposed maintenance planning method is 5012 USD, which is 1.06% of the total maintenance cost.

5.3. Effect of the set-up cost

The economic dependencies are principally represented by sharing of the set-up cost in a multi-component system. Therefore, the effect of the set-up cost on maintenance planning is analyzed in this study. With different set-up costs, the maintenance planning is performed using the proposed method, and the detailed information of the plan obtained is shown in Appendix B.

In general, when the set-up cost is relatively high, such as when set-up cost ranges from 2000 to 8000 USD, only one opportunity is used to limit the number of times to pay the set-up cost. In addition, the higher the set-up cost, the more components that tend to be maintained to share the set-up cost in these cases. When the set-up cost is relatively low compared to the component maintenance cost, the maintenance planner may prefer to use several opportunities for maintenance instead of grouping many maintenance activities in one opportunity. In these cases, the components tend to be maintained at the harbor close to their individual optimum time, such as when the set-up cost is 0 or 500 USD. It is shown that maintaining a component is a trade-off between the set-up cost-sharing and its own maintenance cost.

Fig. 10 represents the maintenance cost saving as a function of the set-up cost. With the same opportunity duration constraints listed in Table 2, the results show that the proposed method provides relatively high maintenance cost savings, especially when the set-up cost is high. In addition, it is intuitive that a higher cost saving can be expected when the set-up cost is higher, as claimed in other studies [22]. The results in the current case show a similar trend as well.

However, special cases occur when the set-up costs are equal to 3000 and 4000 USD in the current case. This is mainly because when considering the economic dependence, the individual optimum maintenance time of a component is tightly linked to the value of the set-up cost. Changes in the set-up cost leads to changes in the individual optimum maintenance time. Since maintenance opportunities are limited and irregular in the case of autonomous ship operation, as the set-up cost changes, the individual optimum maintenance time of certain components may be changed to a time close to the scheduled maintenance harbor. When some components are scheduled in the same harbor according to their own individual optimization process, even if there is no grouping method, the set-up cost is shared. Therefore, although the set-up cost increases, e.g., from 3000 to 4000 USD, the grouping method may not help save much cost compared to a maintenance plan without the proposed method. This is different from the finding when there is no constraint of limited and irregular maintenance opportunities that shown in other studies [22].

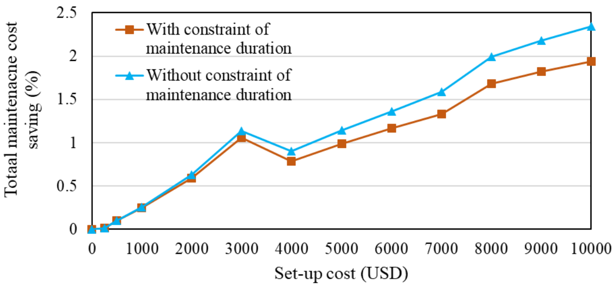

Fig. 10 Maintenance cost saving as a function of set-up cost

Without loss of generality, the situations that without constraints of maintenance duration are tested as well in this section as shown in Fig. 10. It demonstrates the similar trend as described previously.

However, it generally provides more cost-saving compared to the situations with maintenance duration constraints.

5.4. Effect of the grouping horizon in maintenance planning with limited and irregular maintenance opportunities

As mentioned in Section 4.2, previous studies in maintenance grouping usually start with investigating the optimum time to form the first group for maintenance [8, 22, 26]. However, with the constraints of limited and irregular maintenance opportunities, the method that considers only the first opportunity and investigates whether it should be used might be short-sighted.

The current section explores the effect of grouping horizon in the maintenance planning with the constraints of limited and irregular maintenance opportunities. The aim is to test the performance of the proposed methods and validate the proposed heuristic by comparing the results from the proposed method and the "short-sighted" methods with shorter grouping horizon. Three methods with different grouping horizon are investigated: *i*) Only the first harbor is considered at each decision point; *ii*) two foreseeable harbors are considered at each decision point; *iii*) three foreseeable harbors are considered at each decision point (the proposed method in the current study). The information of unconsidered harbors in each method is assumed either unknown to the maintenance planner or ignored by the maintenance planner.

Taking the case study described in Fig. 2 as an example, in method *i*), only Harbor A is considered for maintenance planning at the decision point at t_A. The components that are not maintained in Harbor A will then be maintained at their own individual optimum maintenance time in the future, which is calculated based on the assumption of the average operating and maintenance conditions. The question then becomes to investigate whether Harbor A should be used for maintenance compared to future assumed opportunities based on the average operating and maintenance conditions. If Harbor A should be skipped according to the decision at t_A, the ship will continue the voyage. A new decision on whether to use the opportunity will be made using the same method at Harbor B.

In method *ii*), a similar method is applied, but both Harbors A and B are considered for maintenance planning at the decision point at t_A. The second decision point will be at t_B if both opportunities should be skipped; otherwise, the new decision will be made at Harbor C.

Given the information of the three foreseeable harbors described in Fig. 2 and Table 2, the final maintenance plans according to the different methods can be obtained, as shown in Table 6. In method *i*), Harbor A should be skipped when making decisions at t_A. 300 hours later, Harbor B is decided to be used when making the second decision at t_B. A total of six components in the cooling system need to be maintained. After the group maintenance at Harbor B, there is no need for another maintenance activity at Harbor C.

Table 6 Effect of the number of harbors taking into consideration

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: B	PM: B	PM: C
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	PM: C
6_1	LTFW piping	PM: B	PM: B	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	PM: C
10_1	Main engine charge air cooler	PM: B	PM: B	PM: C

11_1	Generator cooler	Wait	Wait	PM: C
12_1	Gear oil cooler	Wait	Wait	PM: C
13_1	SW piping	PM: B	PM: B	PM: C
14_1	HTFW pump 1 (engine driven)	PM: B	PM: B	PM: C
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: B	PM: B	PM: C
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		6	6	10
Total maintenance cost (USD)		468608	468608	466969

The decision to skip Harbor A using method i) depends on the assumption of average operating and maintenance conditions in the future. Without the actual temporal information of future opportunities when deciding at t_A, simply skipping the current opportunity might be a radical plan because the actual future opportunities might be too far away. Another drawback of the method i) is that it only provides operators and planners with information about whether the current opportunity should be used. If the maintenance plan decides to skip the current opportunity, it fails to notify operators of the next maintenance time. This may lead to logistic difficulties, such as the lack of maintenance resources and insufficient time for maintenance preparation.

In the case of considering two harbors (method ii)), Harbor B is planned to be used when making decisions at t_A. The same maintenance plan as the method i) is obtained. However, by considering one more harbor, the operators have more information to make decisions at t_A. This helps relieve the effect of the unrealistic assumption of the future, and operators can skip the first opportunity with more confidence. Using Harbor B and ignoring the future opportunity might be acceptable; however, it might be too conservative due to the lack of the actual temporal information of future opportunities, which might be much better than the assumed, i.e., it might be closer to individual optimum times of more components than first two harbors.

Taking into account three future opportunities in method iii), the ship can take a greater risk to skip Harbor A and Harbor B, and arrange the maintenance at Harbor C. This plan indicates that the plans in methods i) and ii), in which Harbor B is used, might be too conservative. Without the temporal information of the third harbor, the maintenance plan from methods i) and ii) tend to perform maintenance in one of the foreseeable opportunities, rather than waiting until uncertain future opportunities.

Apart from the advantages of method iii) over methods i) and ii) as mentioned previously, the proposed method (method iii)) also performs better in terms of the total maintenance cost in the current case. Compared to the maintenance plan from methods i) and ii), the maintenance plan from the proposed method provides a lower maintenance cost and can help save the cost of 1639 USD. It should be noted that this saved cost is calculated based on the information of three foreseeable harbors. If further information of future opportunities (e.g., Harbor D) is available when the ship leaves Harbor B, the decision might be updated then. This may help save more money if Harbor D or further opportunity is a better choice than Harbor C.

The results described above show that the proposed method performs better than the other two methods in the current case. To show the effectiveness of the proposed method is universal to different operating situations. Various scenarios with different local ages of components, as shown in Table 7, are developed to further test the effectiveness of the proposed method.

Table 7 Local age/ the states of each component in various scenarios

Id.	Components	Local age x_{i_j} (hrs)/ the states of the component		
		Scenario 1	Scenario 2	Scenario 3
1_1	HTFW piping	300	600	300
2_1	HTFW temperature sensor	15000	15000	6000
3_1	HTFW 3 ways valve	1000	300	700
4_1	HTFW cooler	1000	500	2000
5_1	Expansion tank	100	1500	200
6_1	LTFW piping	450	450	200
7_1	LTFW temperature sensor	2000	2500	300
8_1	LTFW 3 ways valve	2000	1000	500
9_1	Lubrication oil cooler	800	100	100
10_1	Main engine charge air cooler	300	600	200
11_1	Generator cooler	500	300	400
12_1	Gear oil cooler	1000	1000	500
13_1	SW piping	500	300	200
14_1	HTFW pump 1 (engine driven)	25000	25000	6000
14_2	HTFW pump 2 (engine driven)	20000	20000	20000
15_1	LTFW pump 1 (electric driven)	1000	2000	3000
15_2	LTFW pump 2 (electric driven)	500	4000	3000
16_1	Central cooler 1	700	600	2000
16_2	Central cooler 2	700	700	700
17_1	SW pump 1 (electric driven)	8000	8000	2500
17_2	SW pump 2 (electric driven)	7000	2000	3000

Table 8 Maintenance cost of each scenario using different methods

Scenario Num.	Maintenance duration constraint $[D_{t_A}, D_{t_B}, D_{t_C}]$ (hrs)	Maintenance cost (USD)			Saved cost compared to the method *i*) (USD)	Saved cost compared to the method ii) (USD)
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors		
Scenario 0	[200, 200, 200]	468608	468608	466969	1639	1639
	[200, 200, 50]	468608	468608	467933	675	675
	[200, 200, 350]	468608	468608	466628	1980	1980
Scenario 1	[200, 200, 200]	471155	470120	470120	1035	0
	[200, 200, 50]	471155	470120	470120	1035	0
	[200, 200, 350]	471155	470120	470120	1035	0
Scenario 2	[200, 200, 200]	470788	469756	469756	1032	0
	[200, 200, 50]	470788	469756	469756	1032	0
	[200, 200, 350]	470788	469756	469756	1032	0
Scenario 3	[200, 200, 200]	465858	465858	465858	0	0
	[200, 200, 50]	469627	467021	467021	2606	0
	[200, 200, 350]	465569	465569	465569	0	0

Note: Scenario 0 represents the scenario described in Table 3

Table 8 presents the maintenance cost of each scenario using different methods. Various maintenance duration constraints are considered and tested. The detailed maintenance plan of each scenario can be found in Appendix C. With different ages of the component, the maintenance opportunities used and the components considered for maintenance may vary in each plan.

The results show that method *iii*) generally provides a better maintenance plan than methods *i*) and *ii*) in terms of maintenance costs. In the cases where the maintenance duration constraints are the same for each opportunity, method *iii*) performs better because it considers more opportunities' temporal information, e.g., in scenarios 0, 1, 2. Without knowing the actual timing of future opportunities, methods *i*) and *ii*) may provide a conservative plan by using the existing opportunities even though the timing of a future opportunity is more appropriate for grouping maintenance, or provide a radical plan by skipping the existing opportunities even though the future opportunities are far away than assumed.

When the maintenance duration constraint of each harbor is different, method *iii*) may perform even better. When the maintenance duration of the third opportunity is very limited, i.e., 50 hours in this case, method *iii*) may improve the maintenance plan in two ways. Firstly, taking scenario 3 as an example, being aware of the limited maintenance duration at Harbor C, method *iii*) shifts maintenance to an early opportunity at Harbor B. Without knowing the limitations at Harbor C, method *i*) skips the first two opportunities, and decide to use Harbor C when making decision at t_C. However, since the maintenance duration is limited at Harbor C, only a few components can be maintained. This reduces the cost-saving of set-up costs and results in a substantial increase in final maintenance costs, i.e., 2606 USD. Secondly, even though the three methods decide to use the same opportunity, e.g., scenario 0, method *iii*) improves the plan by maintaining more components in an opportunity, given the information that if Harbor C is not used, components can only be maintained after that. Due to the lack of temporal information of future opportunities, methods *i*) and *ii*) prefer to leave some components for future maintenance.

When the third opportunity has longer maintenance duration, i.e., 350 hours in this case, method *iii*) may improve the plan by considering more components for maintenance if Harbor C is decided to be used, e.g., scenario 0. This allows more components to share the set-up cost, thus reducing the total maintenance cost.

In general, the results in this section demonstrate that in the case of limited and irregular maintenance opportunities, the proposed method, i.e., method *iii*) performs better than methods *i*) and *ii*) and provides lower maintenance costs by considering a longer grouping horizon. Without the actual information of future opportunities, "short-sighted" methods, i.e., methods *i*) and *ii*), may not provide acceptable maintenance plans since the actual information of future opportunities can be much better or worse than the assumed. For example, better or worse timing for grouping maintenance, or longer or shorter maintenance durations. This issue can be more obvious when maintenance constraints exist, e.g., maintenance duration. This is because more factors contribute to the maintenance plan in this case and thus the actual information of more opportunities becomes more important. Many maintenance constraints or variables that may affect the maintenance planning in the case of limited and irregular maintenance opportunities, such as various time for each maintenance opportunity, various maintenance teams at each maintenance opportunity, various availability requirement at each period of voyage, are not tested in this study due to limited article length. However, it can be reasonably inferred that all these constraints or variables can largely affect the maintenance planning results.

Therefore, different from the previous studies when there is no constraint of limited and irregular opportunities, considering only the first group and ignoring the potential limitation/advantages of future opportunities are not acceptable. The method that considers two harbors sometimes provide an acceptable result and may strengthen the operators' confidence in the decision of whether to skip the first opportunity, but it may also provide an unacceptable plan in some cases due to the lack of further information. It is shown that with more information on future opportunities, the maintenance plan can be more economical. Table 9 shows the average simulation time of each method. The above simulations are conducted using a personal computer (Intel(R) Core(TM) i7-8665U CPU @ 1.90GHz 2.11 GHz, 16 GB of RAM). The proposed method, i.e., method *iii*), spends 91.87 s on average, which can be considered as an acceptable simulation time given the potential cost saving. Therefore, a longer grouping horizon, i.e., method *iii*) is highly suggested due to its good performance on cost saving and acceptable simulation time.

Table 9 Average simulation time of each method

	Method *i*)	Method *ii*)	Method *iii*)
Average simulation time (s)	11.30	26.42	91.87

However, a grouping horizon with more than three maintenance opportunities is not suggested. Firstly, the simulation complexity and computation grow substantially due to increased number of situations that need to be considered in the maintenance model. Secondly, with the actual information of three opportunities, the proposed method can always make appropriate decisions on whether the first two should be used or not. When the first two opportunities are decided not to be used, a decision can always be updated based on further information of future opportunities (e.g., Harbors B, C, and D when the ship arrives Harbor B). This means that a method with more than three maintenance opportunities is not necessary in terms of cost saving. Lastly, in the case of AMS, the maintenance opportunities are unfixed and irregular, which means that the information of many harbors in the future may not be unavailable. The proposed method is expected to handle a grouping horizon for months (as shown in the case study). Therefore, a grouping horizon with more than three maintenance opportunities is not considered very practical in AMS operation in this sense.

5.5. Testing the proposed method with different operating conditions

The current study proposes a dynamic maintenance planning method for AMS, taking into account the dynamic states of components. the proposed method should be able to use as a general framework of maintenance planning and can be applied to various component status and operating conditions. Different ages of components and maintenance durations have been tested in Section 5.4. In this section, various operating conditions are tested using the proposed method to further demonstrate its versatility.

An important problem that needs to be answered is that if any non-critical components fail, should the ship continue the voyage with the failed components or should the ship stop and schedule for maintenance immediately in a harbor. In addition, once any component fails, the availability of the repairmen who can be brought on board for corrective maintenance is an essential factor for maintenance planning. While other previous studies fail to capture these factors, the problems can be solved by using the proposed method.

Table 10 Failed components in each scenario

Scenarios	Failed component(s)
Scenario 1	Central cooler 1 (#16_1)
Scenario 2	HTFW pump 1 (engine driven) (#14_1)
Scenario 3	HTFW pump 1 (engine driven) (#14_1), SW pump 1 (electric driven) (#17_1)

Considering the three scenarios described in Table 7, it is assumed that some failed components are identified in each scenario, as shown in Table 10. In scenario 1, a central cooler is identified as failed in Harbor A. In scenario 2, one of the HTFW pumps fails. In scenario 3, two components fail, i.e., an HTFW pump and an SW pump. The information about the potential maintenance opportunities and maintenance-related costs are assumed as the same as the previous case study, as shown in Table 2 and Table 4. With identified failed components in Harbor A in each scenario, the availability of the repairmen who can be brought on board for corrective maintenance in Harbor A is considered in maintenance planning. The onboard repairmen are assumed available in Harbor B in all three scenarios. Table 11 demonstrates the maintenance plans for various scenarios obtained using the proposed method.

Table 11 Maintenance plan for each scenario based on the proposed method

Id.	Components	Maintenance plan based on the proposed method					
		Scenario1		Scenario 2		Scenario 3	
		Yes	No	Yes	No	Yes	No
1_1	HTFW piping	PM: B	PM: B	PM: B	PM: A	PM: C	PM: C
2_1	HTFW temperature sensor	PM: B	PM: B	PM: B	PM: A	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait	Wait	Wait	Wait
6_1	LTFW piping	PM: B	PM: B	PM: B	PM: A	PM: C	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: B	PM: B	Wait	Wait	PM: C	PM: C
10_1	Main engine charge air cooler	PM: B	PM: B	PM: B	PM: A	PM: C	PM: C
11_1	Generator cooler	PM: B	PM: B	PM: B	PM: A	PM: C	PM: C
12_1	Gear oil cooler	PM: B	PM: B	PM: B	PM: A	PM: C	PM: C
13_1	SW piping	PM: B	PM: B	PM: B	PM: A	PM: C	PM: C
14_1	HTFW pump 1 (engine driven)	PM: B	PM: B	CM: R	CM: A	CM: R	CM: R
14_2	HTFW pump 2 (engine driven)	Wait	Wait	PM: B	Wait	PM: C	PM: C
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait	Wait	Wait	Wait
16_1	Central cooler 1	CM: R	Wait	Wait	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: B	PM: B	PM: B	PM: A	CM: R	CM: R
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait	Wait	Wait	Wait
Total components need to be maintained		13	13	10	9	10	10
Total maintenance cost (USD)		475964	476128	474048	475060	476164	478023

Note: CM: R represents the corrective maintenance by repairman; Yes and No represents the availability of repairmen that can be brought on board in Harbor A in each scenario

If there are repairmen available in Harbor A and can be brought on board to perform corrective maintenance on the failed components, the ship can skip the opportunity in Harbor A and continue the voyage. This maintenance strategy can be simulated using the Markov model. The transitions in the first phase (from Harbor A to Harbor B) of the multiphase Markov model should reflect the existence of the onboard repairmen during the simulation, as demonstrated previously. When ignoring other components and perform maintenance optimization singly for a KooN subsystem, it is usually economical to maintain it immediately (at Harbor A), even if the onboard repairmen are available. However, as shown in Table 11, when considering other components and taking the economic dependency into account, it is more economical to continue sailing without stopping at Harbor A and perform the corrective maintenance during the voyage in three scenarios. With the different ages of other components in each scenario, different harbors are utilized for maintenance in the plan obtained.

When the repairman is not available in Harbor A to be brought on board, the ship can either stops and perform the maintenance in Harbor A or continue the voyage without a repairman onboard. As shown in Table 11, although the repairman is not onboard, the ship can still skip the Harbor A in scenario 1. The maintenance will still be scheduled in Harbor B, but the failed component is not maintained because the other component in the subsystem is still new, and the maintenance duration is limited. In scenario 2, the maintenance plan totally changes because of the lack of an onboard repairman. The maintenance should be performed immediately at Harbor A, earlier than the plan when the onboard repairman is available. This change is mainly due to the relatively high potential cost of system shutdown incurred by the failed component compared to delaying the maintenance at Harbor B. In scenario 3, the maintenance can still be scheduled in Harbor C. Although the repairman is not available in Harbor A, the ship can continue the voyage and utilize the onboard repairman in Harbor B to perform the corrective maintenance during the voyage after Harbor B. The relatively higher cost is due to potential system shutdown cost during the voyage between Harbor A and B.

The simulation results demonstrate that the proposed method is able to deal with the failed components in the maintenance planning. It can be used as an excellent tool to determine whether the current maintenance opportunities should be skipped when non-critical components fail, either with or without onboard repairmen.

In addition, the total maintenance cost of each scenario, either with or without onboard repairmen in Harbor A, are calculated. It is found that when onboard repairmen are available, bringing them on board is a more economical option. Besides, based on the obtained results, if the cost of onboard repairmen and delay cost in harbor maintenance are available and considered in the maintenance planning, it is easy for operators to determine whether repairmen should be brought on board, or which ship should be prioritized to use the onboard repairmen when more than one autonomous ship require maintenance.

With various scenarios tested, this section demonstrates that the proposed method is able to be used as a framework of maintenance planning in various operating conditions. The results also demonstrate the necessity to explicitly consider different maintenance strategies locally in the maintenance planning, for example, the onboard repairmen. For scenarios with different maintenance assumptions, such as the availability of repairmen and the states of each component, the proposed method shows good applicability by combining the Markov model and grouping method. In addition, other factors such as the cost due to the delayed shipping or the cost due to violating a treaty can also be considered and incorporated into the proposed method for a better decision of the maintenance plan. The current section aims to show the applicability of the proposed framework instead of testing all possible factors. Therefore, not all factors are tested in the current section so as not to dilute the focus of the current work.

6. Conclusions and future work

This study identified the special need for the maintenance planning of AMS and proposed a dynamic maintenance planning method to solve the identified issues. The study claims that three aspects, including dependencies among components, the high consequence of the system failure, and limited and irregular maintenance opportunities, should be considered when performing the maintenance planning of AMS. Considering economical dependencies among components, the study proposed a dynamic grouping method to determine the optimum maintenance opportunity for the AMS from predictable opportunities in the near future. Besides, the stochastic dependencies are considered by using the Markov model. A multiphase Markov model is proposed to deal with the difficulties of limited and irregular maintenance opportunities. By combining the Markov model and grouping method, the proposed method can be used in the maintenance planning of AMS.

A maintenance planning of the cooling system of an autonomous ship is performed as a case study using the proposed method. According to the simulation results, in a total of 10 out of 21 components require preventive maintenance in Harbor C, given three available opportunities in the near future. The results of the case study demonstrate that the proposed method can help to save the cost of 5012 USD in the maintenance of AMS. Some factors that may influence the results of maintenance planning, such as the set-up cost and the grouping horizon that are considered, are also investigated in this work. To demonstrate to the applicability of the proposed method, various scenarios with different component states, opportunity duration and maintenance strategies are tested using the proposed method. Although there is a lack of rigorous mathematical proofs in the heuristic to justify the development of the optimal group structure in this study, scenarios with different set-up costs, operating conditions and grouping horizon demonstrate that the proposed group structure can help to save money in the context of AMS.

Future research work may focus on adapting the proposed method to make use of the real-time data to develop condition-based maintenance planning for AMS.

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Appendix A Development of maintenance planning

Table A.1 Individual optimum time for maintenance

Id.	Component	$t^*_{i_j}$(hrs)
1_1	HTFW piping	3.015E+04
2_1	HTFW temperature sensor	4.234E+04
3_1	HTFW 3 ways valve	3.648E+04
4_1	HTFW cooler	3.622E+04
5_1	Expansion tank	3.175E+04
6_1	LTFW piping	3.030E+04
7_1	LTFW temperature sensor	4.134E+04
8_1	LTFW 3 ways valve	3.598E+04
9_1	Lubrication oil cooler	3.076E+04
10_1	Main engine charge air cooler	3.050E+04
11_1	Generator cooler	3.080E+04
12_1	Gear oil cooler	3.091E+04
13_1	SW piping	3.065E+04
14_1	HTFW pump 1 (engine driven)	3.110E+04
14_2	HTFW pump 2 (engine driven)	3.560E+04
15_1	LTFW pump 1 (electric driven)	3.648E+04
15_2	LTFW pump 2 (electric driven)	3.487E+04
16_1	Central cooler 1	3.470E+04
16_2	Central cooler 2	3.450E+04
17_1	SW pump 1 (electric driven)	3.110E+04
17_2	SW pump 2 (electric driven)	3.794E+04

Appendix B Detailed maintenance plans with different set-up cost

Table B.1 Maintenance plan with different set-up cost

Id.	Component	Maintenance plan					
		S=0	S=500	S=1000	S=3000	S=5000	S=8000
1_1	HTFW piping	PM: A	PM: B	PM: B	PM: C	PM: C	PM C
2_1	HTFW temperature sensor	Wait	Wait	Wait	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait	Wait	Wait	Wait
5_1	Expansion tank	Wait	PM: C	PM: C	PM: C	PM: C	PM: C
6_1	LTFW piping	PM: A	PM: B	PM: B	PM: C	PM: C	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: C	PM: C	PM: C	PM: C	PM: C	PM: C
10_1	Main engine charge air cooler	PM: B	PM: B	PM: B	PM: C	PM: C	PM: C
11_1	Generator cooler	PM: C	PM: C	PM: C	PM: C	PM: C	PM: C
12_1	Gear oil cooler	PM: C	PM: C	PM: C	PM: C	PM: C	PM: C
13_1	SW piping	PM: B	PM: B	PM: C	PM: C	PM: C	PM: C
14_1	HTFW pump 1 (engine driven)	PM: B	PM: B	PM: C	PM: C	PM: C	PM: C
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait	Wait	Wait	PM: C
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: C	PM: C	PM: C	PM: C	PM: C	PM: C
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait	Wait	Wait	Wait
Total components need to be maintained		9	10	10	10	10	10

Appendix C Detailed maintenance plans for each scenario using methods with different grouping horizons

Table C.1 Maintenance plan of Scenario 0 with maintenance constraint [200, 200, 200], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: B	PM: B	PM: C
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	PM: C
6_1	LTFW piping	PM: B	PM: B	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	PM: C
10_1	Main engine charge air cooler	PM: B	PM: B	PM: C
11_1	Generator cooler	Wait	Wait	PM: C
12_1	Gear oil cooler	Wait	Wait	PM: C
13_1	SW piping	PM: B	PM: B	PM: C
14_1	HTFW pump 1 (engine driven)	PM: B	PM: B	PM: C
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: B	PM: B	PM: C
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		6	6	10
Total maintenance cost (USD)		468608	468608	466969

Table C.2 Maintenance plan of Scenario 0 with maintenance constraint [200,200, 50], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: B	PM: B	PM: B
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: B	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	PM: B
10_1	Main engine charge air cooler	PM: B	PM: B	PM: B
11_1	Generator cooler	Wait	Wait	PM: B
12_1	Gear oil cooler	Wait	Wait	Wait
13_1	SW piping	PM: B	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: B	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: B	PM: B	PM: B
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		6	6	10
Total maintenance cost (USD)		468608	468608	467933

Table C.3 Maintenance plan of Scenario 0 with maintenance constraint [200, 200, 350], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: B	PM: B	PM: C
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	PM: C
6_1	LTFW piping	PM: B	PM: B	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	PM: C
10_1	Main engine charge air cooler	PM: B	PM: B	PM: C
11_1	Generator cooler	Wait	Wait	PM: C
12_1	Gear oil cooler	Wait	Wait	PM: C
13_1	SW piping	PM: B	PM: B	PM: C
14_1	HTFW pump 1 (engine driven)	PM: B	PM: B	PM: C
14_2	HTFW pump 2 (engine driven)	Wait	Wait	PM: C
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	PM: C
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: B	PM: B	PM: C
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		6	6	12
Total maintenance cost (USD)		468608	468608	466628

Table C.4 Maintenance plan of Scenario 1 with maintenance constraint [200, 200, 200], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	Wait	PM: B	PM: B
2_1	HTFW temperature sensor	PM: A	PM: B	PM: B
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: A	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: A	PM: B	PM: B
10_1	Main engine charge air cooler	Wait	PM: B	PM: B
11_1	Generator cooler	PM: A	PM: B	PM: B
12_1	Gear oil cooler	PM: A	PM: B	PM: B
13_1	SW piping	PM: A	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: A	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: A	PM: B	PM: B
17_2	SW pump 2 (electric driven)	PM: A	Wait	Wait
Total components need to be maintained		9	10	10
Total maintenance cost (USD)		471155	470120	470120

Table C.5 Maintenance plan of Scenario 1 with maintenance constraint [200, 200, 50], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	Wait	PM: B	PM: B
2_1	HTFW temperature sensor	PM: A	PM: B	PM: B
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: A	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: A	PM: B	PM: B
10_1	Main engine charge air cooler	Wait	PM: B	PM: B
11_1	Generator cooler	PM: A	PM: B	PM: B
12_1	Gear oil cooler	PM: A	PM: B	PM: B
13_1	SW piping	PM: A	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: A	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: A	PM: B	PM: B
17_2	SW pump 2 (electric driven)	PM: A	Wait	Wait
Total components need to be maintained		9	10	10
Total maintenance cost (USD)		471155	470120	470120

Table C.6 Maintenance plan of Scenario 1 with maintenance constraint [200, 200, 350] using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	Wait	PM: B	PM: B
2_1	HTFW temperature sensor	PM: A	PM: B	PM: B
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: A	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: A	PM: B	PM: B
10_1	Main engine charge air cooler	Wait	PM: B	PM: B
11_1	Generator cooler	PM: A	PM: B	PM: B
12_1	Gear oil cooler	PM: A	PM: B	PM: B
13_1	SW piping	PM: A	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: A	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: A	PM: B	PM: B
17_2	SW pump 2 (electric driven)	PM: A	Wait	Wait
Total components need to be maintained		9	10	10
Total maintenance cost (USD)		471155	470120	470120

Table C.7 Maintenance plan for Scenario 2 with maintenance constraint [200, 200, 200], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: A	PM: B	PM: B
2_1	HTFW temperature sensor	PM: A	PM: B	PM: B
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: A	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	Wait
10_1	Main engine charge air cooler	PM: A	PM: B	PM: B
11_1	Generator cooler	Wait	PM: B	PM: B
12_1	Gear oil cooler	PM: A	PM: B	PM: B
13_1	SW piping	PM: A	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: A	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: A	PM: B	PM: B
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		8	9	9
Total maintenance cost (USD)		470788	469756	469756

Table C.8 Maintenance plan for Scenario 2 with maintenance constraint [200, 200, 50], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: A	PM: B	PM: B
2_1	HTFW temperature sensor	PM: A	PM: B	PM: B
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: A	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	Wait
10_1	Main engine charge air cooler	PM: A	PM: B	PM: B
11_1	Generator cooler	Wait	PM: B	PM: B
12_1	Gear oil cooler	PM: A	PM: B	PM: B
13_1	SW piping	PM: A	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: A	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: A	PM: B	PM: B
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		8	9	9
Total maintenance cost (USD)		470788	469756	469756

Table C.9 Maintenance plan for Scenario 2 with maintenance constraint [200, 200, 350], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: A	PM: B	PM: B
2_1	HTFW temperature sensor	PM: A	PM: B	PM: B
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: A	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	Wait
10_1	Main engine charge air cooler	PM: A	PM: B	PM: B
11_1	Generator cooler	Wait	PM: B	PM: B
12_1	Gear oil cooler	PM: A	PM: B	PM: B
13_1	SW piping	PM: A	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	PM: A	PM: B	PM: B
14_2	HTFW pump 2 (engine driven)	Wait	Wait	Wait
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	PM: A	PM: B	PM: B
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		8	9	9
Total maintenance cost (USD)		470788	469756	469756

Table C.10 Maintenance plan for Scenario 3 with maintenance constraint [200, 200, 200], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: C	PM: C	PM: C
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: C	PM: C	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: C	PM: C	PM: C
10_1	Main engine charge air cooler	PM: C	PM: C	PM: C
11_1	Generator cooler	PM: C	PM: C	PM: C
12_1	Gear oil cooler	PM: C	PM: C	PM: C
13_1	SW piping	PM: C	PM: C	PM: C
14_1	HTFW pump 1 (engine driven)	Wait	Wait	Wait
14_2	HTFW pump 2 (engine driven)	PM: C	PM: C	PM: C
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	Wait	Wait	Wait
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		8	8	8
Total maintenance cost (USD)		465858	465858	465858

Table C.11 Maintenance plan for Scenario 3 with maintenance constraint [200, 200, 50], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: C	PM: B	PM: B
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: C	PM: B	PM: B
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	Wait	Wait	Wait
10_1	Main engine charge air cooler	Wait	PM: B	PM: B
11_1	Generator cooler	PM: C	PM: B	PM: B
12_1	Gear oil cooler	PM: C	PM: B	PM: B
13_1	SW piping	Wait	PM: B	PM: B
14_1	HTFW pump 1 (engine driven)	Wait	Wait	Wait
14_2	HTFW pump 2 (engine driven)	Wait	PM: B	PM: B
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	Wait	Wait	Wait
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	Wait	Wait	Wait
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		4	8	8
Total maintenance cost (USD)		469627	467021	467021

Table C.12 Maintenance plan for Scenario 3 with maintenance constraint [200, 200, 350], using methods with different grouping horizons

Id.	Components	Maintenance plan		
		i) One harbor	*ii*) Two harbors	*iii*) Three harbors
1_1	HTFW piping	PM: C	PM: C	PM: C
2_1	HTFW temperature sensor	Wait	Wait	Wait
3_1	HTFW 3 ways valve	Wait	Wait	Wait
4_1	HTFW cooler	Wait	Wait	Wait
5_1	Expansion tank	Wait	Wait	Wait
6_1	LTFW piping	PM: C	PM: C	PM: C
7_1	LTFW temperature sensor	Wait	Wait	Wait
8_1	LTFW 3 ways valve	Wait	Wait	Wait
9_1	Lubrication oil cooler	PM: C	PM: C	PM: C
10_1	Main engine charge air cooler	PM: C	PM: C	PM: C
11_1	Generator cooler	PM: C	PM: C	PM: C
12_1	Gear oil cooler	PM: C	PM: C	PM: C
13_1	SW piping	PM: C	PM: C	PM: C
14_1	HTFW pump 1 (engine driven)	Wait	Wait	Wait
14_2	HTFW pump 2 (engine driven)	PM: C	PM: C	PM: C
15_1	LTFW pump 1 (electric driven)	Wait	Wait	Wait
15_2	LTFW pump 2 (electric driven)	Wait	Wait	Wait
16_1	Central cooler 1	PM: C	PM: C	PM: C
16_2	Central cooler 2	Wait	Wait	Wait
17_1	SW pump 1 (electric driven)	Wait	Wait	Wait
17_2	SW pump 2 (electric driven)	Wait	Wait	Wait
Total components need to be maintained		9	9	9
Total maintenance cost (USD)		465569	465569	465569

Article 5

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UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)

UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
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UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
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MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
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MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
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MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
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IMT- 2011-80	Guo, Bingjie	Numerical and Experimental Investigation of Added Resistance in Waves. Ph.d.Thesis, IMT.
IMT- 2011-81	Chen, Qiaofeng	Ultimate Strength of Aluminium Panels, considering HAZ Effects, IMT
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.
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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
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IMT-9- 2013	Abdillah, Suyuthi	Prediction of Extreme Loads and Fatigue Damage for a Ship Hull due to Ice Action, IMT

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IMT-11-2013	Chuang, Zhenju	Experimental and Numerical Investigation of Speed Loss due to Seakeeping and Maneuvering. IMT
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IMT-14-2013	Haris, Sabril	Damage interaction analysis of ship collisions, IMT
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IMT-17-2013	Gaspar, Henrique	Handling Aspects of Complexity in Conceptual Ship Design, IMT
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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
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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-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
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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-10-2016	Ling Wan	Experimental and Numerical Study of a Combined Offshore Wind and Wave Energy Converter Concept
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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
IMT-2-2018	Sergey Gavrilin	Validation of ship manoeuvring simulation models
IMT-3-2018	Jeevith Hegde	Tools and methods to manage risk in autonomous subsea inspection,maintenance and repair operations
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IMT-6-2018	Bård Stovner	Aided Intertial Navigation of Underwater Vehicles
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IMT-8-2018	Børge Rokseth	Safety and Verification of Advanced Maritime Vessels
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
IMT-16-2019	Drazen Polic	Ice-propeller impact analysis using an inverse propulsion machinery simulation approach
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
IMT-19-2019	Emil Smilden	Structural control of offshore wind turbines – Increasing the role of control design in offshore wind farm development
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
IMT-7-2020	Senthuran Ravinthrakumar	Numerical and Experimental Studies of Resonant Flow in Moonpools in Operational Conditions
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
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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
IMT-12-2022	Siamak Karimi	Shore-to-Ship Charging Systems for Battery-Electric Ships
IMT-01-2023	Huili Xu	Fish-inspired Propulsion Study: Numerical Hydrodynamics of Rigid/Flexible/Morphing Foils and Observations on Real Fish
IMT-02-2023	Chana Sinsabvarodom	Probabilistic Modelling of Ice-drift and Ice Loading on Fixed and Floating Offshore Structures
IMT-03-2023	Martin Skaldebø	Intelligent low-cost solutions for underwater intervention using computer vision and machine learning
IMT-04-2023	Hans Tobias Slette	Vessel operations in exposed aquaculture – Achieving safe and efficient operation of vessel fleets in fish farm systems experiencing challenging metocean conditions
IMT-05-2023	Ruochen Yang	Methods and models for analyzing and controlling the safety in operations of autonomous marine systems