Autonomous Ships from the Perspective of Operation and Maintenance

By

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ABSTRACT

Autonomous ships have been the subject of extensive research and much debate in the maritime shipping community since the turn of the new millennium. Proposed benefits of autonomous ships include reduced fuel consumption, larger cargo capacity, increased safety, improved operational efficiency, and reduced operational costs. If realised to its full potential, autonomous operation could revolutionise the shipping industry. However, as with all new concepts, there are significant uncertainties about its potential and which challenges will arise in the course of its development.

This thesis addresses issues regarding the operation and maintenance of autonomous ships, which will significantly impact their implementation. The thesis is positioned in the technical sciences but also includes non-technical elements. A multi-method approach is used, which includes documentary analyses, field work, interviews, case studies, and mixed-method research. In this thesis, the subject of study is tangible aspects of ship operation, which are often, but not always, associated with autonomous ships – namely increased automation and unmanned operation.

The use of the Reliability Centered Maintenance (RCM) method as a tool for evaluating maintenance and reliability needs on unmanned ships is evaluated, and amendments to the method are proposed. Through case studies, the thesis shows that increased redundancy in machinery systems can significantly reduce the probability of failure on unmanned ships, but redundancy also has its limits. It is found that the uncertain nature of failures, the limiting effect of dependent failures on reliability, and the severely restricted possibilities of corrective maintenance at sea make reliability a very serious obstacle for unmanned ships.

Using data on crew sizes of ships and through interviews with crewing specialists, the thesis finds that the single limiting factor in further reductions in crew sizes is the workload required for operating the ships. Through the analysis of planned maintenance and work time distribution data from conventional ships, maintenance is identified as a poor candidate for automation. The workload related to maintenance is found to be substantial on large ships, and this workload will not be affected significantly by unmanned operation.

The thesis combines data on work time, maintenance, and off-hire incidents to identify different aspects of merchant ship operation that affect the potential for increased automation and unmanned operation. Maintenance is less of a barrier on small ships than on large ships. Transport of passengers is problematic in relation to safety, which makes cargo ships better suited for unmanned operation. Ships on fixed routes are easier to automate than those in the tramp trade. Overall, the potential for automation is considerable for small ships, whereas it is limited for large ships.

Merchant shipping is currently facing important challenges relating to, amongst other things, restrictions on environmental emissions and a shortage of qualified labour. This thesis provides knowledge on the potential and limitations of autonomous operation of ships as a solution to these challenges.

RESUMÉ (DANISH)

Autonome skibe har været genstand for omfattende forskning og stor debat i den maritime verden siden begyndelsen af det nye årtusinde. De forventede fordele ved autonome skibe er bl.a. reduceret brændstofforbrug, større last kapacitet, øget sikkerhed, forbedret driftseffektivitet og reducerede driftsomkostninger. Hvis det fulde potentiale for autonome skibe kan opnås, vil de kunne revolutionere shipping industrien. Som med alle nye koncepter er der dog store usikkerheder om deres potentiale og om hvilke udfordringer der kan forventes i deres udvikling.

Denne afhandling omhandler spørgsmål om drift og vedligehold af autonome skibe, som vil have en betydelig indvirkning på deres implementering. Afhandlingen er positioneret inden for de tekniske videnskaber, men indeholder også ikke-tekniske elementer. Der bruges en multi-method tilgang, som omfatter dokumentariske analyser, feltarbejde, interviews, casestudier og mixed-method forskning. Der undersøges i denne afhandling håndgribelige aspekter af skibsdrift, som ofte, men ikke altid, er forbundet med autonome skibe, nemlig øget automatisering og ubemandet drift.

Anvendelsen af Reliability Centered Maintenance (RCM) metoden som et værktøj til vurdering af vedligeholds- og pålidelighedsbehov på ubemandede skibe evalueres, og der foreslås ændringer til metoden. Gennem casestudier viser afhandlingen, at øget redundans i maskinsystemer kan reducere sandsynligheden for fejl på ubemandede skibe betydeligt, men redundans har også sine grænser. Det konkluderes, at fejlenes usikre karakter, den begrænsende virkning af afhængige fejl på pålidelighed og de stærkt begrænsede muligheder for afhjælpende vedligehold til søs gør pålidelighed til en meget alvorlig forhindring for ubemandede skibe.

Ved hjælp af data om besætningsstørrelser på skibe og gennem interviews med besætningsspecialister finder afhandlingen, at den eneste begrænsende faktor ved yderligere reduktioner i besætningsstørrelser er den arbejdsbyrde, der kræves til drift af skibene. Gennem analysen af planlagt vedligeholds- og arbejdstidsfordelingsdata fra konventionelle skibe identificeres vedligehold som en dårlig kandidat til automatisering. Arbejdsbyrden relateret til vedligehold findes at være betydelig på store skibe, og denne arbejdsbyrde vil ikke blive påvirket væsentligt af ubemandet drift.

Ved at kombinere data om arbejdstid, vedligehold og off-hire hændelser identificerer afhandlingen flere aspekter af driften af handelsskibe, som påvirker potentialet for øget automatisering og ubemandet drift. Vedligehold er en mindre barriere på små skibe end store skibe. Transport af passagerer er problematisk i forhold til sikkerhed, hvilket gør fragtskibe bedre egnet til ubemandet drift. Skibe på faste ruter er lettere at automatisere end dem, der er i tramp-fart. Samlet set er potentialet for automatisering betydeligt for små skibe, mens det er begrænset for store skibe.

Handelsflåden står i disse år over for vigtige udfordringer med blandt andet begrænsninger af miljøudledninger og mangel på kvalificeret arbejdskraft. Denne afhandling giver viden om potentialet og begrænsningerne ved autonom drift af skibe som en løsning på disse udfordringer.

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APPENDED PAPERS

Paper I	Eriksen, S. **Autonomous Ships – Changing Perceptions and Expectations,** *Proceedings of the 18th Conference on Computer and IT Applications in the Maritime Industries, Tullamore, Ireland, 2019*
Paper II	Eriksen, S. **On-board Human Operators: Liabilities or Assets?** *Proceedings of the 19th Conference on Computer and IT Applications in the Maritime Industries, Pontignano, Italy, 2020*
Paper III	Eriksen, S.; Utne, I.B.; Lützen, M. **An RCM approach for assessing reliability challenges and maintenance needs of unmanned cargo ships,** *Journal of Reliability Engineering and System Safety, Vol. 210, June 2021,* DOI: 10.1016/j.ress.2021.107550
Paper IV	Eriksen, S.; Lützen, M. **The impact of redundancy on reliability in machinery systems on unmanned ships,** *(Resubmitted after review 21 August 2021) WMU Journal of Maritime Affairs*
Paper V	Eriksen, S.; Lützen, M. **The impact of unmanned operation of ships on the maintenance workload and related costs,** *(Submitted 16 August 2021) WMU Journal of Maritime Affairs*
Paper VI	Eriksen, S.; Lützen, M. **Manning the unmanned ship: is safe manning legislation a bottleneck in the development of autonomous ships?** *(Submitted 29 May 2021) SN Social Sciences*
Paper VII	Eriksen, S.; Lützen, M.; Larsen, M.B. **On automation and its potential impact on the workload on merchant ships** *(Submitted 8 July 2021) Maritime Policy and Management*

Other contributions during the PhD period

Are autonomous ships manned – and by who? Workshop on the expected future developments of autonomous ships given at CO-Søfart, maritime labour union seminar, April 2019.

Development of autonomous concepts for the commercial maritime sector. Presentation given at Future Surface Fleet Conference, conference on naval surface warfare, June 2020.

Eriksen, S. **Unmanned? Human error and expertise…** Popular science article published in HANSA – International Maritime Journal 01/2021, based on conference paper **On-board Human Operators: Liabilities or Assets?**

Sørensen, J.C.; Eriksen, S.; Lützen, M.; Jensen, J.B. **A Modular Working Vessel Decision Support System for Fuel Consumption Reduction,** International Journal of Information Technology & Decision Making, in press.

CONTENTS

PART III: Appended papers

PART I
Introduction

1 INTRODUCTION

Merchant ships today have the same primary function as when sea transport was first conceived millennia ago: to transport cargo over water from one point to another. However, modern merchant ships are as different from the early wooden boats as a wooden hut is from a skyscraper. The same technological advances that propelled our society into the mechanised and digital age have also transformed the maritime transport industry. Engines replaced sails as the mode of propulsion, and the ships became mechanised in the first industrial revolution towards the end of the 18^{th} century (Schwab, 2017). Electrification and telecommunication came with the second industrial revolution in the 19^{th} century, and the third industrial revolution hailed the advent of microprocessors, computerization and digital communication at the end of the 20^{th} century. Today's merchant ships are larger, safer, more efficient, and can transport more cargo with fewer crew members on board than ever before (Ljung et al., 2014; MacDonald, 2006). More than 10 billion tons of cargo are transported at sea by around 100,000 ships each year, and maritime transport is an essential part of the world economy (UNCTAD, 2020). At the turn of the new millennium, the maritime industry, and the society as a whole, find themselves on the brink of what Brynjolfsson et al. (2014) have called the 'second machine age'; or what Schwab (2017) has described as the fourth industrial revolution or 'Industry 4.0'. This new industrial age is characterised by, amongst other technological trends, the introduction of autonomous vehicles.

Unmanned and fully automated operation of ships is not an entirely new concept but has been the subject of research and debate since at least the 1980s (Bertram, 2003). Recent developments within self-driving cars and other forms of road transport, along with advances in IT, sensor, and communication technology, however, have, since the early 2000s, spurred on renewed interest in the concept, now commonly referred to as autonomous ships. New advances or new projects within autonomous shipping frequently make the headline of maritime news sites see, e.g. CNBC (2018), Pico (2020), and Logan (2021). With political and financial backing for research projects such as MUNIN (2018), AAWA (Rolls-Royce, 2018b), and AUTOSHIP (2021), autonomous ships have also been an important topic in the world of maritime research. Several autonomous ship prototypes are already underway, most notably the Yara Birkeland (Yara, 2020) and the ASKO (Kongsberg, 2020) projects.

Autonomous ships have been heralded by some as the future of the maritime industry, and autonomy is projected to be a technological leap that will revolutionise the landscape of shipping (Jokioinen et al., 2016). The proposed benefits of autonomous ships include reduced fuel consumption, larger cargo capacity, increased safety, improved operational efficiency, and reduced operational costs (Kobylinski, 2018; Rødseth et al., 2012). However, autonomous ships are still a developing concept, and there are still considerable uncertainties regarding what autonomy in shipping will entail, which benefits such vessels will bring, and which challenges will be faced in their development and operation. Legal barriers, data security, and the public perception of autonomous ships are mentioned as severe difficulties (Van Hooydonk, 2014). Skill degradation of operators and errors in the human-machine interface are also perceived to be problematic (Ahvenjärvi, 2016). Reliability of machinery and maintenance of unmanned ships are also seen as significant issues (Jalonen et al., 2017).

Having taken much of its inspiration from road transport, a lot of the interest, research, and development in autonomous shipping have so far been focused on driving automation or, putting it in maritime terms, automated navigation, manoeuvring and collision avoidance (Rødseth et al., 2020; Rolls-Royce, 2018b). Automated navigation is an exciting technical challenge that could fundamentally change the way ships are operated if solved. Because the operation of ships involves a wide variety of tasks, however, automated navigation is only part of the solution for the autonomous ship. This thesis focuses on aspects of autonomous ships relating to operation and maintenance, which have not received much attention in the research so far.

1.1 Motivation

Besides exciting new technologies, the new millennium also presents the world of commercial shipping with a range of new challenges. The global demand for shipping is projected to increase in the coming decades, with a shortage of qualified labour as a result (BIMCO/ICS, 2021; Schröder-Hinrichs et al., 2019). Sustainability and environmental responsibility have become important topics, and commercial shipping is subject to ambitious new goals and demands (IMO, 2021a). New and innovative technologies are needed to meet these new challenges, and it is crucial for the maritime industry to understand if and how autonomous ships can be part of the solution. For the maritime educational institutions to best prepare the new maritime leaders of the future, they need access to the latest knowledge within the field of autonomous ships.

Modern merchant ships are highly advanced mechanical and technical systems that dwarf all other modes of transport in size and cargo capacity – often by orders of magnitude. Keeping these ships in continuous operation requires a considerable and constant work effort by the onboard crew and the shore team. Navigating the ship from one port to the next is one part of the work, but loading, discharging, onboard cargo handling, and operation and maintenance of machinery and systems also require continuous attention and, often, highly specialised skills. Shipping is a highly competitive business. If autonomous technologies can optimise the operation of ships, or if they can minimise or improve the maintenance or the work tasks required for operation in general, it would create massive potential within the maritime transport sector. On the other hand, the need to maintain ships while in active service and the extreme demands for operational efficiency and dependability may be severe barriers to autonomous operation. Research on operation and maintenance-related aspects of autonomous operation is vital for understanding the opportunities that autonomous ships will bring and the challenges faced in their development.

1.2 Outline of Thesis

This thesis is structured as an anthology that includes the work of seven research papers. The thesis consists of three parts. Part I contains sections 1 to 4, in which the subject of the thesis is introduced, the background of the topic of autonomous ships is described, the research questions are presented, and the methods, data, and analysis models used in this thesis are explained. Part II comprises sections 5 to 9 and presents the results and conclusions of this PhD project. In Part III, the seven papers included in this thesis are appended in full length in their published or submitted form.

1.3 ORIGINAL CONTRIBUTIONS

This thesis contributes to the research within the area of operation and maintenance of autonomous ships. The work of this thesis has expanded knowledge of the potential for autonomous ship operation, and barriers to the implementation of autonomy in shipping have been identified. This section summarises the most important original contribution made in the present work.

- An amended Reliability Centered Maintenance (RCM) method for assessing maintenance and reliability issues on unmanned ships has been developed.
- The possibilities and limitations of redundancy in machinery equipment for providing reliable operation of unmanned ships have been shown.
- The effect of voyage length on the reliability of machinery systems of unmanned ships has been demonstrated.
- The impact of unmanned operation on the workload related to maintenance on merchant ships has been established.
- The effects of unmanned operation on the possibility for doing maintenance and the effects of the need for maintenance on unmanned ship operation has been shown.
- It has been shown that legislation on the safe manning of ships is not a bottleneck in the current state of development of autonomous ships.
- The automation potential of the different job tasks required in the operation of ships has been identified, and the overall automation potential of ships of different sizes, types, and forms of operation has been quantified.
- It has been shown how different factors of the operation and construction of ships affect the potential for autonomous operation.
- Potential reductions in the workload by the use of autonomous and/or unmanned operation have been quantified.
- The role of the crew in the occurrence and detection of near-miss incidents and the effect of manned operation on the ability to stop incidents from developing into marine accidents have been established.
- It has been shown that autonomy in shipping is far from a unified established concept and that there are many different perceptions of what defines and constitutes an autonomous ship.

2 STATE OF THE ART

Despite being a relatively new concept, at least in its present form, autonomous ships have been the subject of considerable research within several different fields in recent years. Section 2.1 outlines the most prominent areas of research within autonomous ships. The definition of autonomy, which is still the source of much debate, is explored in section 2.2.

2.1 AREAS OF RESEARCH IN AUTONOMOUS SHIPPING

Navigation has, as mentioned in section 1, been the focus of much of the research within autonomous ships. Autonomous navigation and the use of autonomous or automated systems to navigate according to the international maritime collision regulations (COLREGS) is studied by, amongst others, Stamenkovich (1991), Young-il (2004), Liu et al. (2014), Perera (2018), and Barkhordari et al. (2021). Risk models for autonomous ship navigation are examined by, for example, Thieme et al. (2018) and Blindheim et al. (2020). Computer vision, object detection and object recognition as tools for autonomous navigation are examined by, e.g. Dulski et al. (2011), Blanke et al. (2019), and Becktor et al. (2021).

Existing maritime legislation may be a severe obstacle for autonomous ships, and laws and regulations may have to be amended to allow for autonomous operation. Several studies have focused on regulatory barriers to autonomy in shipping, see, e.g. Van Hooydonk (2014), Carey (2017), Danish Maritime Authority (2017), and Karlis (2018). Many classification societies have also released guidelines or guidance notes on autonomous ships, such as Lloyd's Register (2016), DNV GL (2018), Bureau Veritas (2019), ABS (2020), and ClassNK (2020).

More comprehensive projects encompassing a broader view on the whole concept of autonomous ships from several different angles have also been carried out. Two projects stand out: 'Maritime Unmanned Navigation through Intelligence in Networks', MUNIN (2018), and 'Advanced Autonomous Waterborne Applications', AAWA (Rolls-Royce, 2018b). MUNIN was a three-year project which ended its work in 2016. The European Union-funded project was a collaboration between several European universities and research institutions. The MUNIN project aimed to develop and verify the concept of an unmanned and autonomous bulk carrier in international trade. AAWA was led by Rolls-Royce and involved participants from some of Finland's largest universities and other industry partners. The project, which ended in 2017, explored the economic, social, legal, regulatory and technological factors of autonomy and aimed to produce specifications and preliminary designs for autonomous ships. Both MUNIN and AAWA were conceptual projects aiming to explore the possibilities for the application of autonomous ships and possible barriers to their implementation. The two projects studied the concept of autonomy from a broad and high-level perspective and did not evaluate or aim to develop specific technologies or physical applications. AAWA and MUNIN both identified potential obstacles for autonomous and/or unmanned operation, such as legal barriers and reliability of machinery, but, overall, the projects concluded that there was considerable potential for autonomy in shipping.

At least three projects aiming to build and operate autonomous ships are underway. Yara Birkeland is an electrically propelled container vessel intended for coastal transport (Kongsberg, 2019). The ship is still undergoing construction and testing at the time of writing but is expected to enter autonomous operation in 2022. The second project is a cooperation between the Norwegian grocery distributor ASKO and Kongsberg Maritime. It aims to build two electrically powered Ro-Ro vessels for transporting trailers across the Oslo fjord (Kongsberg, 2020). Most recently, the AUTOSHIP (2021) project combines the conceptual and the practical. The project will explore economic and regulatory barriers and societal issues of autonomous operation of ships and will result in the application of autonomous solutions to two vessels: an inland shipping barge and a short sea cargo vessel. The project is funded by the European Union and runs until the end of 2023.

The perspective of operation and maintenance has received less attention in the research of autonomous ships, but some work has been done. MUNIN (2018) considers necessary changes to autonomous ships' machinery and service systems, including maintenance (Karsten et al., 2013; Schmidt et al., 2015). The AAWA project also discusses issues relating to maintenance and reliability during autonomous operation (Jokioinen et al., 2016). Overall, however, the analyses relating to operation and maintenance in these projects are quite broad and based on rather general assumptions. A few studies have been done on specific aspects of maintenance and reliability of autonomous ships, see, e.g. Rødseth et al. (2016), Allal et al. (2017), and Abaei et al. (2021). Some work has been done, but overall, the operation and maintenance of autonomous ships have not received much attention, and there are still many important unanswered questions.

Despite the extensive public and academic interest in autonomy, both in the maritime domain and in a broader context, there is no unified definition of what autonomy entails for a technical system (Rødseth et al., 2020, Myhre et al., 2019). Considerable work has been done on the definition of autonomous ships or what autonomy in shipping entails, and the discussion is still ongoing, see, e.g. Clough (2002), Vagia et al. (2016), Rødseth et al. (2017), Myhre et al. (2019), Rødseth (2019), Rødseth et al. (2020) and Rødseth et al. (2021). The issue of how autonomy in shipping is defined is expanded on in section 2.2.

2.2 DEFINING AUTONOMY

Because autonomy and the autonomous ship is the subject of research in this thesis, it is crucial to have an understanding of the present state of research and the discussion surrounding the definition of these terms. This section discusses the most commonly used definitions of autonomy in shipping found in the existing literature.

The different areas of research described in section 2.1 naturally investigate the concept of autonomous ships from different viewpoints, but they also tend to have different perspectives on what defines them. Multiple different definitions have been proposed, which each focuses on these different aspects of autonomy (Vagia et al., 2016). When used consistently, each of these definitions can accurately delineate what is meant by autonomy within a specific area of focus or research. When moving across different research fields, such as in this thesis, the delineation becomes difficult since the various definitions do not align with each other. A ship or a system may be designated as autonomous in one field using one definition but be described as non-autonomous in another field using another definition.

The core definition found in, for example, the Oxford English dictionary describes autonomy as *'the ability to act and make decisions without being controlled by anyone else'* (Hornby et al., 2005). Autonomy in this pure form is, in practice, virtually unattainable for any entity since the decisions and actions of all organisms, companies, nations, or machinery systems are affected by external inputs in some way (Rødseth et al., 2020). All workable definitions of autonomy used in a technical context relate to this core definition to some extent, but they also differ to varying degrees. The existing definitions of autonomy generally revolve around three qualifiers, namely: self-governance, sensing and planning, and independence from an operator. These three qualifiers focus on different aspects of autonomous ships and relate to different aspects of the core definition. The qualifiers fall into a spectrum of being 'weak', in the sense that they are global, non-specific and inclusive, or 'strong' in the sense that they are restrictive and specific, as described by Beer et al. (2014) and Rødseth et al. (2020). All three qualifiers have strengths and weaknesses.

2.2.1 Self-governance

The qualifier that comes closest to the core definition of autonomy is self-governance. This qualifier focuses on the part of the core definition relating to the freedom to make decisions, which implies that an autonomous system must have agency and freedom to act outside predefined limits (Intel, 2018). Self-governance or machine cognition is part of some definitions, see, e.g. Antsaklis et al. (1991), Vagia et al. (2016) and ABS (2020). One particularly notable and often quoted definition that revolves around self-governance is that of Rødseth et al. (2017):

> *'Autonomy is the result of applying 'advanced' automation to a ship so that it implements some form of self-governance, i.e. that it can select between alternative strategies without consulting the human.'*

The benefit of self-governance as a qualifier is that it is close to the core definition. As is the case with the core definition, the weakness of using self-governance as a qualifier in a technical system is that it may not be practically attainable (Intel, 2018). Self-governance is a very strong qualifier, and it may, in effect, exclude all technical systems (Rødseth et al., 2020). It is also questionable if self-governance is desirable since it would make the actions of such a system inherently non-deterministic (Rødseth et al., 2012). Having a ship that does not follow orders or mission plans is clearly not desirable (Rødseth et al., 2020).

Another sub-category of self-governance as a qualifier for autonomy is that of legal accountability, as suggested by Myhre et al. (2019):

> *'A system is considered autonomous if it can legally accept accountability for an operation, thereby assuming the accountability that was previously held by either a human operator or another autonomous system.'*

The idea is alluring as it moves the evaluation from what has been shown to be a complicated technical issue to a legal assessment where a system is autonomous if it fulfils a strict legal requirement. It would also pre-empt many of the legal issues of the operation of autonomous and/or unmanned ships as investigated by, e.g. Carey (2017), Van Hooydonk (2014), and the Danish Maritime Authority (2017). As a qualifier, legal accountability is very restrictive, and the idea of a machine being a legal entity that can be held accountable according to the law is, in practice, a pretty futuristic prospect (Calverley, 2008). Legal accountability is usually reserved for humans; even animals – who, it can certainly be argued, possess self-governance – cannot be held legally responsible for a criminal act because they lack moral agency (Taylor, 2009). As a qualifier for autonomy, legal accountability has not gained much attention.

2.2.2 Sensing and planning

The ability for a system to sense its environment and plan future actions based on the measured inputs is often mentioned as a feature of an autonomous system and is sometimes used as a qualifier for this, see, e.g. Bekey (2005), or this excerpt taken from Beer et al. (2014):

> *'The extent to which a robot can sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal (either given to or created by the robot) without external control.'*

This qualifier does not attempt to define autonomy globally but is tailored to mobile robots operating in non-restricted environments. As a qualifier, sensing and planning can be perceived as both weak and strong because it relies on other terms that are, themselves, not clearly defined (Rødseth et al., 2020), which is also the weakness of this type of definition. Sensing, for example, is hard to quantify as even very simple automated processes often rely on external inputs, thus sensing the environment in some form (Rødseth et al., 2020). Planning can also mean different things. Simple feedforward control, which is used in many basic control processes (Haugen, 2010), can be argued to be some form of planning. On the other hand, planning could also imply a conscious decision process, in which case the issue is the same as discussed regarding self-governance. Environmental complexity is sometimes added as an additional qualifier to the complexity of the sensing and planning but evaluating this complexity is, in itself, difficult (Rødseth et al., 2020).

2.2.3 Independence from operator

The ability to operate independently from an operator is perhaps the most common qualifier for autonomy, see, e.g. Rødseth et al. (2018) and MASRWG (2020). Many sources use definitions similar to that adopted by the IMO (2020):

> *'In the context of ships, autonomy e.g. as in 'Autonomous Ship', means that the ship uses automation to operate without human intervention, related to one or more ship processes, for the full duration or in limited periods of the ship's operations or voyage.'*

Independence from an operator, such as used in this definition and many others, is the weakest of the qualifiers (Rødseth et al., 2020), and its inclusive nature is perhaps both its strength and weakness. Autonomy would be attainable for many systems using this definition, but it is very hard in practice to distinguish autonomy defined in this way from automation in even its simplest form. Automation is also defined based on its ability to operate independently from an operator, such as this from the ISO (1992) '*Automation: Pertaining to a process or device that, under specified conditions, functions without human intervention*'. What separates autonomy from automation in these two definitions is only that the former must be designed and verified to be able to operate for some specified period. Because the definition does not make any distinction regarding the complexity of the automation, any unsupervised automated process could potentially be described as autonomous if it can meet the verification criteria (Rødseth et al., 2020). Even the most basic merchant ship today contains numerable unsupervised automated processes. An example of such a process, for which the term autonomy is presumably not intended, is a simple cooling water thermostat used in all ship's engines (Rødseth et al., 2020). On smaller ship engines, this thermostat is an entirely mechanical part, comparable in function and complexity to a radiator thermostat in a home. The thermostat is placed inside the engine, completely inaccessible to an operator during operation, where it can run reliably and unattended for years without human intervention. If such a simple automated process could meet the definition of autonomy, all ships could, in effect, be defined as autonomous.

3 RESEARCH FOCUS

This section describes the focus of the research in the present thesis. Section 3.1 describes how the concept of autonomous ships is understood in this thesis and which parts of their operation are studied in the present work. This understanding of the autonomous ship described in section 3.1 forms the basis for the focus areas and the research questions presented in section 3.2, on which the work in this thesis is built.

3.1 AUTONOMY IN THE PRESENT THESIS

Each of the different definitions of autonomy presented in section 2.2 has its application and may be used consistently within an individual area of research. Finding a globally unified definition of autonomy in shipping, however, has proven very difficult. The use of the term autonomy in shipping is not clear and concise, as the exploration of definitions in section 2.2 shows and as concluded by others such as Beer et al. (2014). According to Rødseth et al. (2020), it is very difficult to find a definition that clearly distinguishes between the terms 'autonomy' and 'automation' and, according to Vagia et al. (2016), there is no consistent way of using the two terms.

Because the definition is not well established, and because it has transformed from the core definition presented in section 2.2, some question whether the term 'autonomous' should be used to describe automated or technical systems at all. SAE International (2021) take the position that autonomy in this context is a misnomer and should not be used to describe the automated driving of cars as is their focus area. Others like Rødseth et al. (2020) argue that it is better to keep the term because the discourse surrounding autonomous ships is already well established. This thesis recognises that 'autonomous' may not be a useful technical term, but it also acknowledges that it is widely used in the maritime world.

To this effect, the term 'autonomous' is maintained but used sparingly throughout the thesis and appended papers. This thesis researches tangible aspects of ship operation, which are often, but not always, associated with autonomous ships – namely increased automation and unmanned operation. It is also primarily these terms that are used to describe the studied scenarios and cases. Because this thesis contributes to the ongoing research into what is commonly described as autonomous ships, the word autonomous is therefore maintained but is only used as a broad, overarching term. This thesis will not make any assessment of which of the many existing definitions of autonomy is the most appropriate or correct; nor will it attempt to construct its own definition of autonomy or autonomous ships. The phrasing of the research questions, which is presented in section 3.2, reflects this specific focus on unmanned operation and increased automation.

3.2 FOCUS AREAS AND RESEARCH QUESTIONS

This thesis investigates aspects of autonomy in shipping relating to 'operation' and 'maintenance'. Besides these two focus areas, the thesis also examines the aspect of 'automation and redundancy'. Each of the three focus areas, also shown in Figure 1, play a crucial role on conventional ships today, and they must be addressed in the development of the highly automated and unmanned ships of the future.

Unmanned operation and increased automation will likely affect the need for **'automation and redundancy'** in machinery equipment. On the one hand, some failures caused by human errors may be avoided. On the other hand, more redundancy in equipment may be needed if the crew cannot handle failures at sea.

'Maintenance' is defined by CEN (2010) as a *'combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function'.* Correct and timely maintenance is essential for the safe and reliable operation of ships.
'**Operation'** refers to the way ships are run, e.g. how much time they spend respectively at sea, in port, at anchor, or which type of cargo they carry or if they engage in tramp, liner, or route trade. The specific operation of the ships is likely to have a significant impact on the possibilities and potential for unmanned operation and increased automation. The competitiveness and profitability of merchant ships depend on the efficiency of their operation, and unmanned operation and increased automation may affect the operational efficiency of merchant ships in both positive and negative ways.

The three focus areas can be considered as independent subjects with a shared basis in autonomy, and they could be treated separately, but the areas also intersect, as shown in Figure 1. If the parameters of one focus area change, it will therefore affect the others, so to reach the most holistic understanding of autonomous ships from the perspective of operation and maintenance, this thesis examines the three focus areas together.

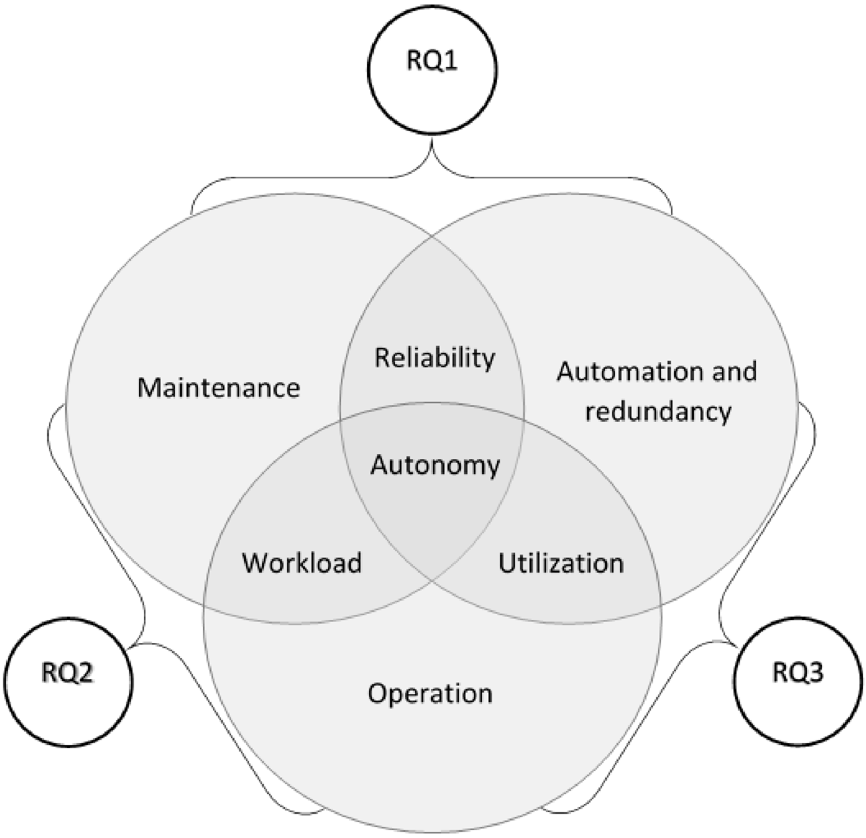

Figure 1 Main areas of focus and research questions of this PhD project

'Utilization' is positioned between the two focus areas of 'operation' and 'automation and redundancy'. Without the need to accommodate a crew on board, the ships might be utilized more efficiently. On the other hand, the absence of a crew may require more work to be done in port, which could extend port operations and have a negative effect on the operation of the ships.
'Reliability' is found at the juncture between 'automation and redundancy' and 'maintenance'. Unmanned operation and increased automation may affect the reliability of machinery systems which might require a

different level of automation and redundancy. Maintenance is affected by the required level of automation and redundancy in machinery equipment, and the level of automation and redundancy in machinery is also affected by the ability to do maintenance during autonomous operation.
'Workload' lies at the intersection of the focus areas of 'maintenance' and 'operation'. The workload required to maintain modern merchant ships is considerable, and the need to do maintenance on an autonomous ship could interfere with its operation. Autonomous operation, on the other hand, could also reduce the workload required for maintenance or affect the way maintenance is done on ships in other ways.

Based on the three focus areas and their intersections, this thesis poses three research questions. The research questions focus on unmanned operation and increased automation of ships, as detailed in section 3.1. The three research questions on which this thesis is based are:

How will unmanned operation and increased automation affect -

> **RQ1: - the reliability and need for redundancy of merchant ships?**
> **RQ2: - the workload required for operating and maintaining merchant ships?**
> **RQ3: - the operational patterns and utilization rate of merchant ships?**

The three research questions presented here form the foundation of this thesis and the seven appended papers. Each of the appended papers focuses on different aspects, but they are linked together by the three research questions that revolve around the central theme of autonomy in shipping, as seen in Figure 1. The results presented in Part II and the conclusions presented in section 9 are also structured around the three research questions presented in this section.

4 METHODOLOGY

This section describes the methodology, data, and methods used in the present thesis. Section 4.1 describes the overall methodological approach of the thesis, and the methods and data used in the appended papers are summarised in section 4.2.

4.1 OVERALL METHODOLOGICAL APPROACH

The work described in the present thesis and appended papers does not fall directly into one particular research field. The PhD project is at its core technical but also crosses over into non-technical themes such as human error and legislation, and the overall methodology reflects this broad perspective. The overarching research philosophy in this PhD project can be described as pragmatism (Saunders et al., 2009), where the best available methods are used to answer the research questions based on the best available data. The work has a predominantly deductive drive focusing on theory or hypothesis testing, but it also makes more generalisable findings of a more inductive nature. A selection of mainly quantitative methods is used in the appended paper. As a combined work, this thesis can be described as primarily utilizing a multi-method approach (Creswell et al., 2003). However, qualitative elements have also been used to complement the quantitative analyses, and the thesis thus contains elements of the mixed-method research approach described in brief in section 4.1.2. A qualitative element, which was included from the beginning and which helped shape the project as a whole, is that of explorative expert interviews.

4.1.1 Explorative interviews

In the explorative phase, expert interviews (Bogner et al., 2009) were used to crystalize the project's focus. Four interview sessions were conducted between February and May in 2019, in which five industry experts from the shipping companies Lauritzen Kosan, DFDS, and Maersk were interviewed. The interviewees held leadership roles in the companies within digital solutions, innovation, data analytics, fleet management, or technology, and all were or had previously been involved in projects looking at aspects of autonomy in shipping. The interviews were informal and semi-structured. Notes were taken during and after the interview, but as they were not intended to result in publishable data, and in the interest of maximum openness by the interviewees, they were not recorded. The interviews focused on the present state of development of autonomous ship projects in the shipping companies and the future interest in this development. Questions were also asked regarding the personal expert opinion of the interviewees on the concept of autonomous ships and the expectations, benefits, and perceived barriers to the development of these. The interviews were used to align the focus of this thesis and the formulation of the research questions so that the findings will be of general interest to the shipping industry. Also, the interviews were used to explore which data sources would be beneficial to explore in the project and which data would be possible to access. Access to the research field was also expanded through the interviews.

4.1.2 Mixed-method research approach

With its combination of quantitative and qualitative analyses, the present thesis makes use of the mixed-method research (MMR) approach. MMR originated in the social sciences but has since expanded into other fields, such as health and medical science (Hesse-Biber, 2010). The exact definition of what MMR constitutes and how it differs from, for instance, multi-method research varies, but the term MMR is typically reserved for studies that include the collection and analysis of both qualitative and quantitative data. MMR can be used to triangulate results by analysing the same dataset using different methods, or it can be used to complement the results of, e.g. a quantitative study with the qualitative analysis of related data. These two approaches are reflected in the two standard MMR designs: the convergent design, where the qualitative and quantitative analysis results are merged, or the sequential design, where the results of one analysis are used to build on the other (Creswell et al., 2003). The sequential design can be either explanatory or explorative. In the explanatory design, the results of the qualitative analysis are used to interpret the results of the quantitative analysis. In the explorative design, the qualitative analysis is used to identify a feature for testing through a quantitative analysis.

An explanatory sequential mixed-method approach is used explicitly in Paper VI, as further described in section 4.2.6. Features of the explorative approach are utilized by the inclusion of expert interviews as a means to solidify the research focus of the present thesis, as described in section 4.1.1.

4.2 Data and Methods

The broad research focus of the present thesis is reflected in the choice of data and methods in the appended papers. Multiple types of data and several different methods have been used. This section summarises the data and methods used in the seven appended papers. Please refer to the appended papers in Part III for specific details of the methods and data used in each paper.

4.2.1 Paper I

This paper explores the perception of autonomous ships using documentary material from scientific literature, research projects and news sources, which is collected using a conceptual literature review (Stratton, 2019). All amended papers involve a literature study to determine the state-of-the-art, but in Paper I, the literature also forms the data source for the analysis. The documentary material is examined with regards to how it defines autonomy or how it describes properties of autonomous ships using document analysis (Bowen, 2009).

4.2.2 Paper II

Paper II examines the effects of the onboard crew in the precursor events of maritime accidents, the so-called near-miss accidents. The source of data in Paper II is near-miss reports, and the reports are examined using document analysis (Bowen, 2009). Near-miss reports are analysed with regards to how the role of the crew is described in the occurrence and detection of near misses.

4.2.3 Paper III

This paper focuses on analysing the applicability of one specific method, the Reliability Centered Maintenance (RCM) method, for use on unmanned ships. Amendments are proposed based on the analysis, and the use of the amended RCM method is verified in a case study. The case study uses reliability data from the OREDA reliability data handbook (SINTEF, 2002) and maintenance data from the Planned Maintenance System (PMS) of cargo ships.

4.2.4 Paper IV

Paper IV investigates the effects of redundancy and unmanned operation of ships on reliability in machinery systems. The paper uses a case study to examine the effect of the length of unmanned sea voyages on the probability of failure in machinery systems with redundancy. A case study is also done on the effect of dependent failures on reliability. Data from the OREDA reliability data handbook (SINTEF, 2002) is used in the case studies.

4.2.5 Paper V

Paper V examines the impact of unmanned operation of ships on the maintenance workload. The paper uses case studies to investigate how maintenance work tasks will be needed to a lesser or a greater extent on permanently or periodically unmanned ships. The primary source of data in the paper is maintenance records from the Planned Maintenance System (PMS) of five cargo ships. Data on the operation pattern obtained from records on the operational activities of the same five ships are also used. The work time distribution of the crew of one of the five ships, the source of which is explained in more detail in section 4.2.7, is also included.

4.2.6 Paper VI

This paper uses an explanatory sequential mixed-method approach, as described in section 4.1.2, to examine whether legislation on safe manning is a bottleneck in the reduction in crew sizes of ships. Quantitative manning data of ships are used to determine differences between the required minimum safe manning and the actual manning sizes of ships. These differences are explained through qualitative expert interviews with manning specialists from the Danish Maritime Authority and the shipping companies Lauritzen Kosan and TORM. The semi-structured interview form was chosen as it allowed for an exploratory but structured examination of the topic.

4.2.7 Paper VII

Paper VII explores the automation potential of merchant ships and its possible impact on the workload required for their operation. The paper proposes and applies a model for evaluating the automation potential of different categories of work on ships. The categories and the work time distribution were captured using observations and interviews with crew members during field studies on four ships. Specific details of the fieldwork, the work time distribution data, and the ships on which the work was done can be found in Paper VII. Fieldwork is a labour-intensive and resource-demanding method of data collection, but it was prioritised to ensure the most complete and exact responses. Other less time-intensive and resource-demanding methods, such as questionnaires, were initially considered, but it was found that the relative complexity of the division of work time categories and the risk of missing or partial responses required a physical face-to-face approach.

PART II
Results

PART II STRUCTURE

Part II presents the results of this thesis, and it is structured into five sections. Figure 2 shows the structure of sections 5 to 8, in which the results of the seven amended papers are presented and discussed. Section 9 presents the conclusions of this thesis. Figure 2 shows how the work of the seven papers relates to each of the four sections. Section 5 includes the work of Paper I and describes the different perceptions of what an autonomous ship is. The findings of section 5 form the basis of how autonomy and autonomous ships are discussed and described in the remaining sections and thus encompass the whole thesis as indicated in Figure 2.

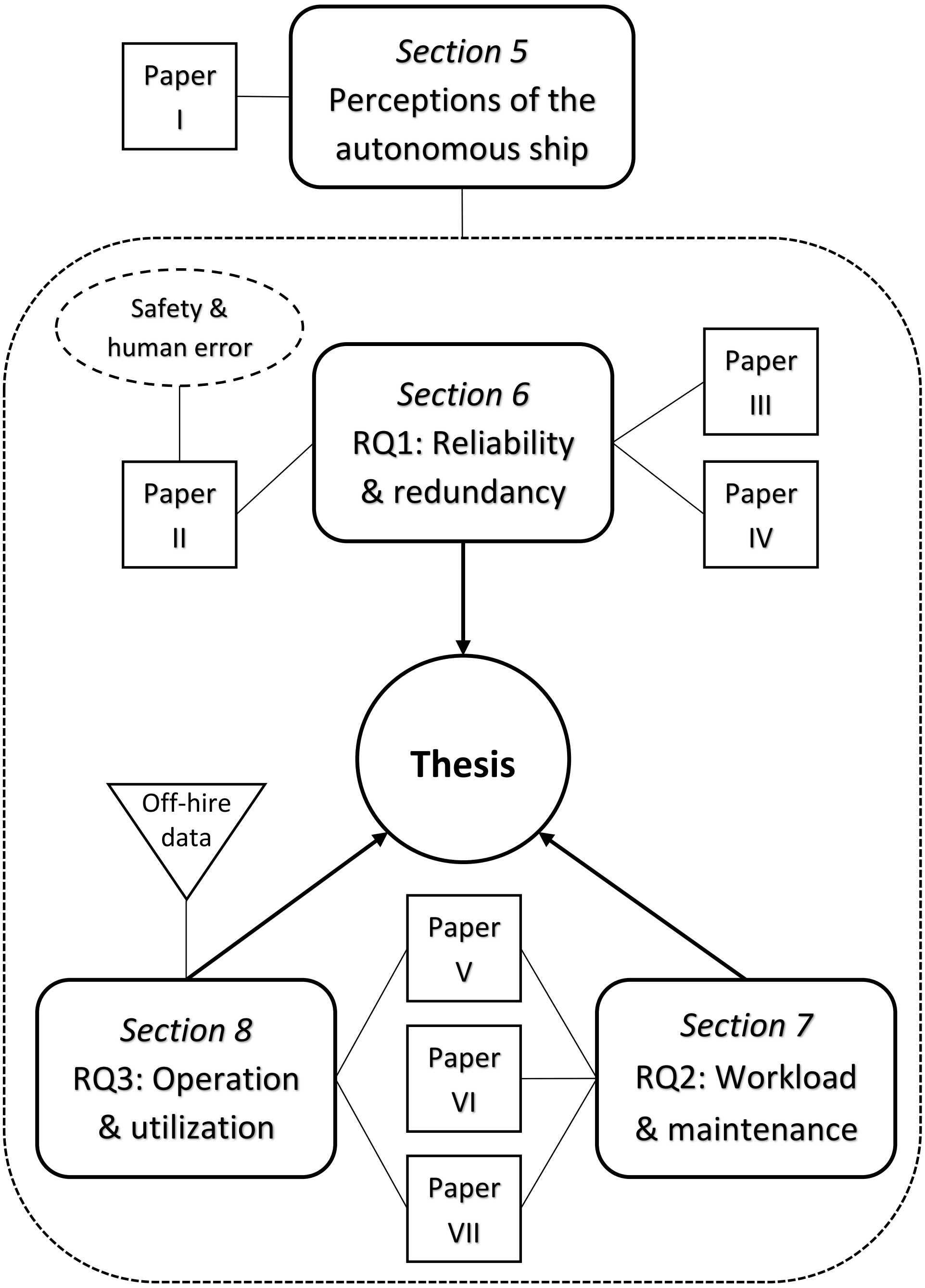

Figure 2 Structure of Part II: Results

Sections 6, 7, and 8 are structured around the three research questions presented in section 3.2. Research question 1 is explored in section 6, which includes the works of Papers II, III, and IV. The main contribution of Paper II is knowledge on safety and human error, which is not explicitly addressed in this thesis, but the findings of this paper also relate to research question 1, regarding reliability and redundancy. Section 7 considers research question 2 regarding workload and maintenance and includes the work of Papers V, VI, and VII. The work of Papers V and VII is also the foundation of section 8, which explores research question 3 on operation and utilization. Also included in section 8 is data on off-hire events that has not found its place in any of the amended papers nor been published elsewhere in this thesis. The off-hire data supplements the findings of Papers V and VII by showing the effects of the onboard crew on interruptions to the operation of conventionally manned ships.

5 PERCEPTIONS OF THE AUTONOMOUS SHIP

Autonomous ships have not been fully introduced in the maritime industry, and the perception of what constitutes an autonomous ship may not yet be completely solidified. The definition of autonomy in shipping is still a point of contention, as section 2.2 shows, but this could be a purely semantic discussion. The autonomous ship could be a unified concept that looks different from the various research areas because they look at it from different angles. The ambiguity surrounding the definition could, on the other hand, also be indicative of a more general uncertainty of the nature of autonomous ships and what they are supposed to be. Perhaps the definitions do not converge because the different research areas are not looking at the same ship but rather a collection of separate concepts that are each described as autonomous. The autonomous ship may be one unitary concept that is simply difficult to define, or it could be a collection of separate concepts that may be difficult to combine into one.

This section describes the perceptions of the autonomous ship and the differences and uncertainties in these perceptions. Paper I investigates the origin of the term autonomy in a maritime context, how the term is used, how this use has changed over time, and which consequences result from the ambiguity in the use of the term. A summary of Paper I is given here. The perception of the autonomous ship is discussed more broadly in section 5.2.

5.1 PAPER I

In Paper I, the perception of what autonomous ships are and how this perception has changed over time is investigated. The paper analyses documentary material from research projects, scientific publications and news articles. Material from the two largest research projects within the autonomous and/or unmanned shipping is studied, namely 'Maritime Unmanned Navigation through Intelligence in Networks', MUNIN (2018), and 'Advanced Autonomous Waterborne Applications', AAWA (Jokioinen et al., 2016). Paper I analyses 12 scientific papers describing different aspects of autonomous and/or unmanned operation of ships and 23 news articles from maritime and business news sites. The material is analysed with regard to:

- How is autonomy defined, and what characterises the autonomous ship?
- How is the term automation used in relation to autonomy?
- What are the expected benefits of the autonomous ship?
- What are the expected challenges in developing and operating the autonomous ship?

The two projects provides the most detailed description of the autonomous ship. The scientific papers investigate different aspects of the autonomous ship; a definition is sometimes given, but the concept of the autonomous ship is rarely described in detail. No definitions are given in the news articles but they typically describe single features, benefits, or challenges of the autonomous ship.

MUNIN investigates the case study of an autonomous and/or unmanned bulk carrier, whereas AAWA focuses on the broader concept of autonomous ships. Despite the slightly different focus, there are many similarities in how the autonomous ship is perceived. In the context of MUNIN and AAWA, an autonomous ship is an unmanned ship with a high level of automation and redundancy. The ship is continuously monitored; it may be remotely operated from a shore control centre, and it likely requires dynamic positioning capabilities. Both projects claim to distinguish between an autonomous and an unmanned ship, but they also frequently use the two terms interchangeably or imply features of one aspect when describing the other. In about half the scientific papers, and in the majority of the news articles, autonomous and unmanned are used synonymously. In the news articles, the terms automation and autonomous are frequently used interchangeably.

The benefits expected of autonomous ships across all sources are increased safety; a reduction in accidents due to elimination of or reduction in human error; better operational efficiency; lower operational costs and, particularly, lower crew costs; higher reliability; and the elimination of the need for an accommodation resulting in better fuel consumption, lower build costs and less maintenance. AAWA also expect that data coming from the autonomous ships will enable more effective pooling, allowing for new leasing opportunities and better cargo services. Route and weather route planning is also expected to be optimised as well as improved maintenance scheduling and machine diagnostics.

Legislative barriers are the most frequently mentioned challenge in the development of autonomous ships. Also often mentioned in the news articles is the yet unproven business case. Data accessibility and data security are mentioned across all sources. Skill degradation of operators, human-machine interface and poor situational awareness is mentioned in the two projects and the scientific articles. MUNIN highlights technical robustness and a possible need for extended port stays to accommodate for maintenance work as challenges.

The general conclusion of Paper I is that some features of the perception of autonomous ships are shared, but there are also significant differences. Most notably, there is no agreement on whether an autonomous ship is also an unmanned ship. The connection between autonomous and unmanned operation is rarely stated outright, but it is implied in many cases, or the two terms are used synonymously or interchangeably. Whether an autonomous ship is also unmanned is important because most expected benefits and challenges are related to the absence of an onboard crew. It is also found that the terms autonomy and automation are frequently used synonymously and that there is no common consensus on whether remote operation can be described as autonomous operation.

5.2 Discussion - Perceptions of the autonomous ship

Unlike previous technological advances such as the introduction of the steam or diesel engine or the implementation of the shipping container, to which the autonomous ship is often compared, autonomy is not in itself a technology. Instead, autonomy is a collection of existing technologies used in a new way in the same way as Uber® and Airbnb®, for example, have used existing computer technology to change the way many people travel (Levander, 2017). A technology is not autonomous in the same sense that a technology is either digital or analogue, for example. There is no inherent property that makes a technology autonomous, just as there is typically no inherent property that makes a technology ‘green’ or environmentally friendly. Technologies are ‘green’ or autonomous because they are used for that purpose. What constitutes a containership is its ability to carry containers and what constitutes a motorship is its motor, but what constitutes an autonomous ship if it cannot be identified by a specific technology? How do we distinguish an autonomous ship from a non-autonomous ship? As it turns out, these questions are not trivial.

Autonomy has been used to describe technical systems in other domains for decades. In industry, where it has been used at least since the 1980s, the term is typically used to describe mobile robots (Podnar et al., 1984). In unmanned underwater or aerial vehicles, the term autonomous is used to distinguish from those that are remotely controlled by an operator (Noma, 2016, Gupta et al., 2013). The term autonomy is used extensively to describe self-driving cars (Siemens, 2020), although the use of the term in this context is contested by some (SAE International, 2021). Autonomy in these domains does not translate directly to autonomous ships, but they share some common aspects. Especially the recent advances in driving automation of cars, or road vehicles in general, are often linked to autonomous ships (Wahlström et al., 2015; ABS, 2020; Allianz, 2017). Driving automation has also been mentioned as the inspiration for the current focus of research within autonomous or automated navigation capabilities of ships (Levander, 2017; Rahav, 2017).

The ability to navigate without continuous supervision and interaction from a human onboard is by many considered to be what constitutes autonomy in ships (Rødseth et al., 2018; Levander, 2017; Porathe et al., 2013). For many others, such as in the definition by IMO (2020) shown in section 2.2, navigation is not decisive for autonomy. In this perception, a ship is autonomous if any of the processes onboard uses automation that is designed and verified to operate without human intervention for a specified period, even if the bridge is continuously manned as on ships today. Paper I shows that the autonomous ship is also very often perceived to be an unmanned ship, even though unmanned operation on a ship level is not part of any of the definitions discussed in section 2.2.

Instead of the binary view of a ship being either autonomous or not, some propose that autonomy should be considered on a scale. Lloyd's Register (2016) has proposed such a scale which is frequently quoted, and IMO (2021b) has also, at least provisionally, proposed an autonomy scale in their regulatory scoping exercise. The scales categorise ships into levels, typically between no autonomy and full autonomy. Unmanned operation typically constitutes a level or part of a level. Other factors can include remote control and fully automated operation. Using the scale perspective, most or all ships can thus be described as being autonomous to some degree. However, not all agree with this approach and argue that ships should only be designated as autonomous when they fulfil the requirements for full autonomy (Bureau Veritas, 2019). DNV GL (2018) proposes using the term 'autoremote' for functions below the level of full autonomy. Yet others contend the designation of a ship as being autonomous altogether. Rather than considering autonomy on an overall ship level, ClassNK (2020) advocates that the evaluation and designation of autonomy should only be applied to the individual function of the ship. In this interpretation, there would be no such thing as an 'autonomous ship'; only a ship with autonomous functions.

Apart from understanding autonomy as an identifiable and measurable feature that adheres to the individual ship and distinguishes autonomous from non-autonomous ships, there is also a broader, more contextual view. In this context, autonomous ships are described in more general terms to be a movement, an idea, a new paradigm, or a new way of designing and operating ships (WMU, 2019). Autonomous ships are, when described from this perspective, often described as being synonymous with smart, intelligent, or connected ships as also described in Paper I. Autonomous ships should be seen not as individual ships but as a part of a larger interconnected network of ships, which can also involve ports and other intermodal transport facilities (WMU, 2019). In this broader interpretation, autonomy may not be a distinct, identifiable feature of a ship. Autonomy becomes an intangible quality in the same way as one can talk about the industrialised society or the digital age, without necessarily having a measure of when a society becomes industrialised or when an age becomes digital.

Overall, there are many different perceptions of what constitutes an autonomous ship. This lack of a common viewpoint is problematic because assertions made in one area of research with one perspective cannot be effectively evaluated by others with a different perspective. Perhaps this conflict in the perception of the autonomous ship is one reason for the continued uncertainty surrounding the definition of autonomy in a maritime context.

6 RQ1: Reliability & redundancy

Unmanned operation of ships is likely to have both positive and negative impacts on the reliability and safety of ships. On the one hand, human error is a contributing factor in the majority of maritime accidents (Allianz, 2017). Breakdowns, incidents, and accidents may be reduced if human attentiveness and working memory are replaced or supplemented with automation. The presence of an onboard crew may, on the other hand, also enable the detection and prevention of developing incidents and failures, and the crew may play a role in mitigating the consequences of these. Without an onboard crew, more monitoring, detection, and remote operation equipment may be needed to operate safely. Paper II investigates this issue by analysing incidents that were close to developing into serious accidents, the so-called near-misses.

If the unmanned ships of the future are to be at least as safe as the conventionally manned ships of today, as suggested by e.g. de Vos et al. (2020), there may be a more general need for greater redundancy in machinery systems because of the restricted possibilities for doing corrective maintenance during unmanned operation. Methods for objectively evaluating the reliability of machinery systems on unmanned ships must be developed. Paper III evaluates whether the Reliability Centered Maintenance (RCM) (Moubray, 1997) method would be suited to this purpose and suggests amendments to the method for it to better apply to unmanned ships.

Reliability of machinery has been identified by several as a serious challenge to unmanned and/or autonomous operation of ships, see, e.g. Rødseth et al. (2014), Rødseth et al. (2015), and Abdelmoula et al. (2017). Redundancy is typically suggested as a solution to improve reliability. There may, however, be a limit to which level of reliability can be reached through redundancy (Downer, 2009). Unmanned operation will likely require higher reliability but unmanned operation itself may have a negative effect on reliability. Paper IV investigates this issue through case studies of reliability in redundant systems.

This section addresses the research question on how unmanned operation and increased automation will affect the reliability and need for redundancy of merchant ships. A summary of Papers II, III, and IV is given here, and the research question is discussed as a whole in section 6.4.

6.1 PAPER II

Paper II investigates how unmanned operation will impact the ability to detect and prevent near-miss incidents from developing into marine accidents. Human error is a factor in most marine accidents, and a frequently mentioned expected benefit of unmanned operation of ships is the elimination or at least reduction of human error. Human actions, however, also prevent and mitigate the consequences of accidents. By analysing reports on near-miss incidents from ships, Paper II investigates the role of the onboard crew in the occurrence and detection of incidents as well as the role of crew in stopping incidents from developing into maritime accidents.

Out of an initial pool of 7,205 near-misses, 481 were evaluated to have the potential to develop into a marine accident and were selected for further analysis. Near-misses were then categorised into three near-miss types: 'fire', which comprises 40 per cent of the reports; 'flooding' comprising 36 per cent; and 'contact' making up the remaining 24 per cent. The position of the ships at the time of the incident was noted. A significant finding of which was that only 8 per cent of 'contact-related' near-misses, e.g. collisions with other ships, occurred when the ships were in open sea. Similar to other analyses on this topic, the scenario chosen for the unmanned ship in Paper II is that the ship is manned or remotely controlled when not in open sea, i.e. during manoeuvring, at anchor or in port. Unmanned operation can therefore only be expected to have a small impact on 'contact-related' accidents.

In the next step, it is analysed whether the near-misses are discovered by human presence, which is the case for 87 per cent of near-misses, or by an alarm or measuring point. The cause of the incidents is also analysed, and the near-misses are grouped into 'human error', 'equipment failure' or 'external influence', the latter meaning another ship, object or an extreme meteorological event. Human error is the cause of between 29 and 45 per cent of near-misses. Equipment failure is responsible for most of the 'fire' and 'flooding-related' near-misses, but only 14 per cent of those related to 'contact'. Nearly half of 'contact-related' near-misses, but virtually none relating to 'fire' and 'flooding', are caused by external influences.

In the last step of the analysis, an evaluation is done on the effect of unmanned operation on the possibilities for stopping the near-miss from escalating into an accident. The analysis shows that almost all 'fire-related' and 'flooding-related' near-misses would be more difficult to stop on an unmanned ship, although it would be possible to contain but not repair about half the incidents. Because the ship is assumed to be either manned or remote controlled during nearly all 'contact-related' near-misses, the possibility of stopping the development of these into accidents is barely affected.

Paper II concludes that human error is an important factor in the occurrence of near-misses. However, it is also found that humans are instrumental in both detecting and stopping the near-misses from developing into accidents. Many incidents would still happen on an unmanned ship, but they would be more difficult to detect and harder to stop. This indicates the need for significantly more monitoring and failure detection equipment on ships under unmanned operation. Some near-misses and accidents are caused directly by onboard human error that could be prevented if tasks could be automated. However, still missing from the data are incidents and accidents that will be caused by the introduction of unmanned operation. Whether unmanned operation will result in a net decrease or increase in the number of incidents and accidents is still uncertain and will depend entirely on the technical capabilities of the unmanned ships of the future. On today's modern merchant ships, however, with the existing technical systems, humans are vital in both the detection of incidents and the ability to stop the development of incidents into accidents.

6.2 PAPER III

In Paper III, the Reliability Centered Maintenance (RCM) method is analysed as a tool for assessing reliability challenges and maintenance needs on unmanned cargo ships. Amendments to the RCM method are suggested, and the amended method is applied in a case study of a cooling water system.

Reliability of machinery equipment will be an important issue on unmanned ships because of the severely restricted possibilities of carrying out corrective maintenance when at sea. However, traditional maintenance strategies do not consider the reliability of the ship systems and sub-systems as a whole. Originally developed for the aviation industry and since used in many other businesses, RCM has been suggested as a suitable method for meeting these challenges. Paper III evaluates the applicability of RCM in this context and finds that the method is generally applicable to the examination of reliability and maintenance issues on unmanned ships, but there are also important limitations.

The RCM method lacks a systematic process for evaluating the effects of preventive versus corrective maintenance measures. Many corrective maintenance tasks are implicitly included in the operational scenario, and the effects of these corrective maintenance tasks are not as visible as the preventive maintenance tasks explicitly resulting from the RCM analysis. A more structured way of assessing the effects of corrective maintenance tasks is therefore proposed in Paper III. The RCM method also lacks a procedure to ensure that the effect of the length of the unmanned voyage in the development of potential failures in machinery systems is included. Long periods of unmanned operation pose unique challenges for the assessment of the reliability of machinery systems. On long unmanned voyages, it will often not be possible to do corrective maintenance actions in the ‘timely manner’ assumed in the conventional RCM method. Therefore, a method is proposed for assessing the impact of long unmanned voyages on the development of failures in systems with redundancy before the system can be accessed and repaired.

The amended RCM method is tested on a case study of a real cooling water system. An RCM analysis is carried out for two situations: one where the cargo vessel is conventionally manned and one where it is unmanned. No key differences were found in the proposed preventive maintenance tasks between manned and unmanned operation. However, significant differences were found in the possibilities for performing corrective maintenance between manned and unmanned operation, because corrective maintenance primarily depends on the ability of the onboard crew to make physical repairs. Without humans present on the unmanned cargo ship at sea, the possibilities for performing corrective maintenance are severely restricted, which seriously impacts the consequences of failures. Increased redundancy in some form is found to be necessary for all the analysed equipment units to achieve an acceptable risk level on unmanned cargo ships. Design changes that reduce the risk level to an acceptable level are proposed. The risk is found to be manageable with design changes to the unmanned cargo ship for the analysed system but is not found to be lower for unmanned operation than for manned operation in any scenario. The main difference between manned and unmanned operation regarding reliability is found to be the greatly differing possibilities for corrective maintenance actions. This presents a significant challenge for the unmanned operation of commercial cargo ships.

6.3 PAPER IV

Paper IV examines the effect of voyage length on the reliability of machinery with redundancy on unmanned ships. This issue was first encountered in the work with Paper III but is further explored and expanded upon in this paper. The limiting effects of dependent failures on the improvement of reliability through the use of redundancy are also explored.

Modern cargo ships and their machinery systems are very advanced. Ships are constructed not as a unitary whole but as a combination of individual equipment units or equipment systems originating from several different suppliers. These systems are at the same time highly interconnected. Main engines on large ships, for example, are typically not self-contained units but rely on external systems for cooling, fuel cleaning, lubrication, etc. A failure in any of these systems could result in a loss of propulsion, but many of the equipment units making up these systems are, at the same time, not very reliable. Redundancy is used extensively to improve reliability and will be even more crucial on unmanned ships, but there are limitations to the level of reliability that can be achieved through redundancy in real applications.

Reliability is probabilistic and time is always a factor. The longer any equipment unit runs, the higher the probability of failure will be. In standby-redundant configurations, one or more equipment units are ready to take over when the operating unit fails. On conventionally manned ships, the failed unit can, in most cases, be brought back to a functioning state by the onboard crew, and the voyage length would therefore not affect the reliability of the system as a whole. The possibility of corrective maintenance on unmanned ships at sea is severely restricted, and if units fail during the voyage, they must likely remain in a failed state until the ship can be accessed by repair personnel at the next port. Voyage length, therefore, has an influence on the reliability of systems with redundancy on unmanned ships.

Paper IV analyses the effect of voyage length on the probability of failure on unmanned ships in a case study using pumps as an example. The paper considers the case of two pumps in a standby-redundant configuration and finds that the probability of experiencing independent failures of both pumps increases with voyage length by a factor almost directly proportional to the voyage length. The probability of two independent failures on a fourteen-day voyage is almost fourteen times higher than on fourteen one-day voyages in the analysed scenario. This issue is easily solvable by adding additional redundancy that, although it does not resolve the issue, can reduce the probability of all units failing independently to infinitesimally small values.

Besides the probability of experiencing independent failures, there is also a different and separate probability of experiencing a dependent failure. In dependent failures, all redundant units are affected by the same event and fail simultaneously. Dependent failures are not affected by voyage length but are especially critical on unmanned ships because of the significantly restricted possibilities of doing corrective maintenance at sea. Paper IV evaluates a case where only 1 per cent of failures are dependent failures, and 99 per cent are independent. It is found that when even a slight possibility of dependent failures is considered, the contribution of this to the total probability of failure easily surpasses the contribution of independent failures. It is widely recognised that reliability of machinery will be an issue on unmanned ships. Increased redundancy is often proposed as the solution but, as Paper IV shows, this is only effective for independent failures. Redundancy can greatly improve reliability, but because of dependent failures, there is an upper limit to the extent of this improvement. Without a crew onboard to repair equipment when it fails, other solutions besides redundancy may be needed. Paper IV also remarks on the issue of increased automation and complexity needed for unmanned operation in itself becoming a source of unreliability. Complexity is typically considered the antithesis of reliability.

6.4 Discussion - Reliability & redundancy

Modern merchant ships are large, complex and rely on multiple separate but interconnected machinery systems. Commercially operated ships are constructed to be safe and reliable, but they are also built in an open and competitive market where costs play an important role. Merchant ships are ‘workhorses’ that are able to operate continuously for years, but the equipment units making up these ships systems are often not very reliable. As the findings of Papers II, III, and IV show, redundancy plays a large part in making this possible. The three papers also show the effects of an onboard human presence on the reliability and how without it much more monitoring and remote-control equipment, as well as more redundancy in equipment, will be necessary. Lastly, and potentially very troubling for unmanned operation, the papers also show that there are limits to which level of reliability can be achieved by redundancy.

The present work supports the finding of others that reliability of machinery equipment is a serious barrier towards unmanned operation and that more redundancy of machinery equipment will be needed on unmanned ships, see, e.g. Rødseth et al. (2014), Rødseth et al. (2015), and Abdelmoula et al. (2017). Reliability in itself is not the problem per se. Only minor differences are found in the reliability between systems on manned and unmanned ships, as described in Papers III and IV. For unmanned ships to be as safe as manned ships, an equivalent level of risk must be achieved (de Vos et al., 2020, DNV GL, 2018). Risk can be described as the product of probability and consequences (ABS, 2018). While the probability of failure, in this case, mechanical failure to machinery, is not found to be markedly higher on an unmanned ship, the consequences of failures are found to be much more severe because of the severely restricted possibilities for doing corrective maintenance when at sea.

These findings are an indication of the deeply ingrained role of humans in the operation of ships. Conventional merchant ships are not designed for unmanned operation, and they would not remain operable for long without a crew. Being such a fundamental part of the operation, it is perhaps easy to overlook the role of humans in day-to-day operation. The RCM method evaluated in Paper III is a good example of this. Although the original method was applicable to the analysed case in many ways, it was not found to be very good at isolating the actions of humans, and amendments were therefore proposed to this effect. In most other cases, no such distinction would be necessary because the human presence can simply be assumed, and corrective actions can be implicitly included in the operational scenario. The analysis of near-miss reports in Paper II also highlights the vital role of ship crews in preventing and detecting accidents.

Poor reliability of equipment and systems is manageable on manned ships because humans are there to intervene. When automation or mechanical systems fail, humans are there as a fall-back mechanism. The need for fall-backs is recognised for autonomous/automated navigation where humans are typically kept in the loop to some extent up until the step which is typically described as ‘full autonomy’, see, e.g. Lloyd's Register (2016), ABS (2020), and IMO (2021b). Engine rooms on modern merchant ships already work in this way. The engine room is unmanned outside regular working hours, but an engineer is alerted if an alarm or measurement point exceeds a predetermined value. For unmanned operation, the problem is that mechanical failures often require physical intervention on the ship and, unlike for navigation-related issues, very little can be done remotely.

Without a human presence to mitigate the consequences, the probability of failure must be reduced to maintain an equivalent level of risk. Increased redundancy can, to a large extent, provide this, but as Paper IV shows, it does have its limitations. As shown in multiple examples, such as the near-catastrophic incident of the cruise ship ‘Viking Sky’ mentioned in Paper IV, dependent failures are very difficult to predict.

Failures in seemingly redundant and isolated systems happen despite the best efforts of system designers. Increased automation and redundancy may somewhat paradoxically exacerbate this issue instead of making it better, as discussed in Paper IV. The relationships between components multiply dramatically when systems become more complex, and their interactions become much harder to understand and predict. Complexity may in itself become a source of unreliability (Jones, 2012).

Paper III and Paper IV both discuss the use of online condition monitoring and predictive maintenance as a method to avoid or reduce failures. Condition monitoring is already widely used on modern merchant ships, and further developments in sensor technology, advanced failure detection algorithms and maritime data communication are likely to advance its use in the future, but the methods also have their limitations. Not all failures have measurable failure indicators, and those that do must still be detected in enough time to intervene before the failure occurs (Moubray, 1997). The cost of sensors and monitoring equipment must, of course, also be balanced with benefits. Condition monitoring and predictive maintenance may benefit all ships, but whether autonomous operation will enable it depends on how autonomy is perceived. Unmanned operation is not conducive to the use of condition monitoring as many of the techniques require human presence, handheld equipment and/or partial disassembly of equipment units, as Paper IV explains. The more conceptual understanding of the autonomous ship as one that encompasses artificial intelligence, machine learning, remote monitoring and advanced diagnostics may dramatically improve the use of predictive maintenance.

Despite better condition monitoring, remote diagnostics and predictive maintenance techniques, many failures are likely to continue to occur at random intervals. This uncertainty is very problematic for automated and unmanned systems. Without humans onboard, the operational consequences from failures in machinery will increase. Redundancy can provide increased reliability but only up to a certain level. Besides adding to the costs, more redundancy also adds to the complexity, contributing to more random and dependent failures (NASA, 2008). This de facto limit to the achievable reliability of machinery systems by redundancy in combination with the inherently probabilistic nature of failures is a very serious obstacle for unmanned shipping.

7 RQ2: WORKLOAD & MAINTENANCE

Autonomous operation of ships is expected to have several benefits, of which reductions in crew sizes, or in some cases eliminating the onboard crew altogether, is one of the most frequently mentioned, as Paper I shows. There may be other reasons to reduce the crew sizes, such as safety, but there is little doubt that the economic benefit of reduced crew costs is a significant factor (MacDonald, 2006). Moving work from the ship to shore may have benefits of its own, but it does not in itself reduce the workload and related labour costs. If the full economic benefit is to be achieved, the workload must also be reduced.

Housing a permanent crew on board a ship requires an accommodation and a wide range of hotel systems such as air-conditioning, sewage, provision storage and refrigeration, etc. An unmanned ship would not need these systems, the maintenance required for their upkeep would not be required, and the workload could therefore be reduced. If the accommodation of the crew in itself creates a significant workload, this will provide an economic incentive for moving other work tasks ashore. Unmanned operation would, however, as shown in section 6, also require more redundancy of machinery equipment, – which would contribute to increasing the workload required for maintenance. Paper V explores the impact of unmanned operation on the workload required for maintaining modern merchant ships.

Legal barriers are often mentioned as a serious hurdle in the development of autonomous ships, and the relationship between maritime law and autonomous ships has been the subject of several studies, see, e.g. Van Hooydonk (2014), Carey (2017), and the Danish Maritime Authority (2017). Minimum safe manning of ships is regulated by national and international laws (IMO, 2000) and reducing the crew sizes not only has to be economically and practically viable; it must also be legally possible. There would not be any incentive for a shipowner or operator to invest in advanced automation that would enable reductions in the workload if legal barriers prevent a reduction in the crew size. Paper VI investigates to which extent the law of minimum manning is preventing reductions in crew sizes.

Modern merchant ships can transport more cargo with fewer accidents, smaller crews and higher efficiency than ever before. Automation has played a leading role in this development (MacDonald, 2006), and increased automation is also the driving force behind the current developments towards autonomous and/or unmanned shipping. Not all parts of the ship's operation, however, have equal potential for automation. Paper VII examines the automation potential of the different parts of ships operation and to which extent automation can reduce the workload on different types of merchant vessels.

This section addresses the research question on how unmanned operation and increased automation will affect the workload and the manning required for operating and maintaining merchant ships. A summary of Papers V, VI, and VII is given here, and research question 2 is discussed as a whole in section 7.4.

7.1 Paper V

Paper V examines whether the workload of maintaining modern cargo ships can be expected to decrease or increase if the ships are to operate unmanned. On the one hand, the maintenance burden may decrease when the systems and amenities needed for accommodating a crew onboard the ship are no longer needed. On the other hand, an unmanned ship will most likely need more redundancy in machinery systems because of the dramatically reduced possibility for corrective maintenance during sea passages. This paper uses data from the Planned Maintenance System (PMS) of five ships to examine whether these two factors will result in a net increase or decrease in the maintenance workload.

A total of 26,433 maintenance jobs done over three years and four months combined operation time is used in the analysis. Data on the distribution of the work time and data on the operation of the five ships are also used in the analysis. The maintenance jobs are categorised based on whether they relate to equipment that is used for the accommodation of the crew or whether they would still be needed on an unmanned ship.

Two cases of unmanned operation are proposed. In case 1, the ship is always unmanned at sea and cannot accommodate a crew at any time. All maintenance must therefore be done when the ship is in port. There are no systems for the accommodation of a crew, nor are there any lifesaving appliances. Because a repair crew must be able to enter the ship in port and carry out maintenance safely, there must be some manual firefighting equipment and other amenities such as electrical power, compressed air, water, etc. In case 2, the ship is normally unmanned but has the option to accommodate a repair crew when at sea. The systems needed for the accommodation of a crew and the lifesaving appliances must therefore be present but in a reduced size and/or capacity compared to a conventional ship. More manual firefighting equipment than in case 1 but less than for a conventional ship must be present. The other amenities mentioned in case 1 must also be present.

In both unmanned cases, more redundancy of machinery is required. Because the ship in case 2 must be able to operate unmanned, it must have the same level of redundancy as in case 1. In the unmanned cases, it is assumed that the main engine (ME), steering gear and rudder arrangement is duplicated in their entirety. It is further assumed that the duplication of the ME and steering gear does not affect the interval or duration of the maintenance jobs related to them. Any maintenance jobs done on the singular ME, steering gear, and rudder arrangement on the conventionally manned ship must therefore be done on both units in the unmanned cases, and twice as much total time must consequently be allocated for the maintenance of these units when they are duplicated.

The analysis of the maintenance tasks shows that 74.1 per cent of the maintenance work time is spent on systems not affected by unmanned operation. Only 6.5 per cent of the maintenance work time is spent on systems directly related to the accommodation of the crew. However, an additional 7.5 per cent is spent on lifesaving appliances, which is also affected by unmanned operation. The other two categories affected by unmanned operation, 'Manual firefighting equipment' and 'Communication equipment', only constitute smaller parts of the work time.

When the systems and amenities needed for accommodating a crew do not need to be maintained, the workload will be reduced by 18 per cent in case 1 and 10 per cent in case 2. However, the increased need for redundancy will add 14 per cent to the workload in both cases. In total, there is a net decrease in the maintenance workload of 4 per cent in case 1 but a net increase of 4 per cent in case 2. Overall, the workload will remain largely unchanged regardless of unmanned operation, and the cost of this work cannot be counted towards potential savings in crew costs on unmanned ships.

7.2 Paper VI

Paper VI investigates to which extent legislation on manning levels on ships is a current stopping block in the gradual reduction in crew sizes going towards unmanned operation. The so-called minimum safe manning levels on ships are determined by the flag states in which the ships are registered. As the name suggests, ships are not allowed to operate with a smaller crew than the minimum safe manning dictates. The incentive for the shipowner to invest in technologies that would allow for reductions in the crew size will be limited if the law does not allow for such reductions.

Paper VI uses data on minimum safe manning and actual manning from 210 merchant ships of different types, sizes, and operational patterns to investigate how close the actual manning levels are to the safe manning levels. The paper also investigates which factors determine these manning levels through interviews with crewing managers from two Danish shipping companies and a safe manning specialist from the Danish Maritime Authority (DMA).

The study finds that the actual manning level is higher than the minimum level required by law for 97 per cent of the ships in the analysis. The actual crew size exceeded the safe manning by 33 per cent or more on 78 per cent of the ships, and on 49 per cent of the ships, it exceeded the safe manning by 50 per cent or more. Not surprisingly, a strong correlation between ship size and both actual and minimum crew size is found. It is also found that the largest ships have the largest difference between the minimum and actual manning. Ro-Ro passenger ships of less than 1000 GRT had both the smallest minimum and actual crew sizes and the smallest difference between the two. All six ships in the analysis where the crew was not larger than required by law were found in this group. Large Ro-Ro passenger ships of more than 1000 GRT, on the other hand, have both the largest crews and the largest differences between safe and actual manning, some exceeding 150 per cent. This suggests that the size of the ship plays a bigger role in the crew size than the ship type or operational pattern.

Both interviewees from the shipping companies point to crew costs as a significant financial expense constituting, as a rule of thumb, about 2/3 of the total operational expenses within their segments. They also explain that manning levels and crew costs on their ships are not different from that of their competitors. Both interviewees agree that there is a clear economic and competitive incentive to reduce crew size and crew costs but point to a lack of technical systems making this possible. According to the interviewees, the actual crew sizes of the ships were larger than the required because the workload onboard dictates it. Neither company interviewees saw any other challenges, legal or otherwise, in the reduction in crew sizes within the boundaries of safe manning. None of the three interviewees was aware of or saw the introduction of any new technologies that could reduce the manning level significantly in the near future, and all shared the view that the reduction in crew sizes in the near future would be minor.

The interviewee from the DMA explained that the safe manning levels are not static but could be reduced within the existing regulatory framework if technical systems enabling a reduction in the actual crew size were to become available in the future. All interviewees see the development moving towards unmanned and/or autonomous operation but also see this as being many years off, especially for large commercial cargo ships. The paper concludes that fully unmanned operation is unlikely to be possible under current legislation. However, the existing legislation on safe manning does allow for dramatic reductions in crew sizes for the large majority of ships. In general, legislation on safe manning is therefore found not to be a bottleneck in the present state of development of autonomous and unmanned ships.

7.3 Paper VII

This paper explores the automation potential of commercial cargo and passenger ships and its possible impact on the workload required for their operation. The work required to operate modern merchant ships is different from other forms of transport to which ships are often compared. For example, a car or a road truck, for example, is typically operated by one person who is almost entirely engaged in driving the vehicle. Conventionally manned ships are operated by several crew members, typically around 20 for larger ships, of which the manoeuvring and navigation is only part of the work carried out on board during operation. Five work time categories are identified in Paper VII, which describes the work done on modern merchant ships: Navigation, Shipboard operation, Maintenance, Administration, and Catering & Hotel service.

Paper VII uses data from field studies on four ships of different types, sizes, and operation patterns: a gas tanker, a Ro-Ro and a small and a large Ro Pax. Crews on the four ships were interviewed on which onboard work tasks the ship's operation involves and how their work time is distributed within the five work time categories.

Based on existing literature, the paper identifies positive and negative automation indicators. Using these indicators, the automation potential of each work time category is evaluated. The 'Navigation' category is evaluated to have a high automation potential. 'Shipboard operation' is evaluated to have medium automation potential. The automation potential of the last three categories, – 'Maintenance', 'Administration' and 'Catering & Hotel service', – is evaluated as being low.

Next, the distribution of work time in the five categories is introduced. The results are shown in Figure 3.

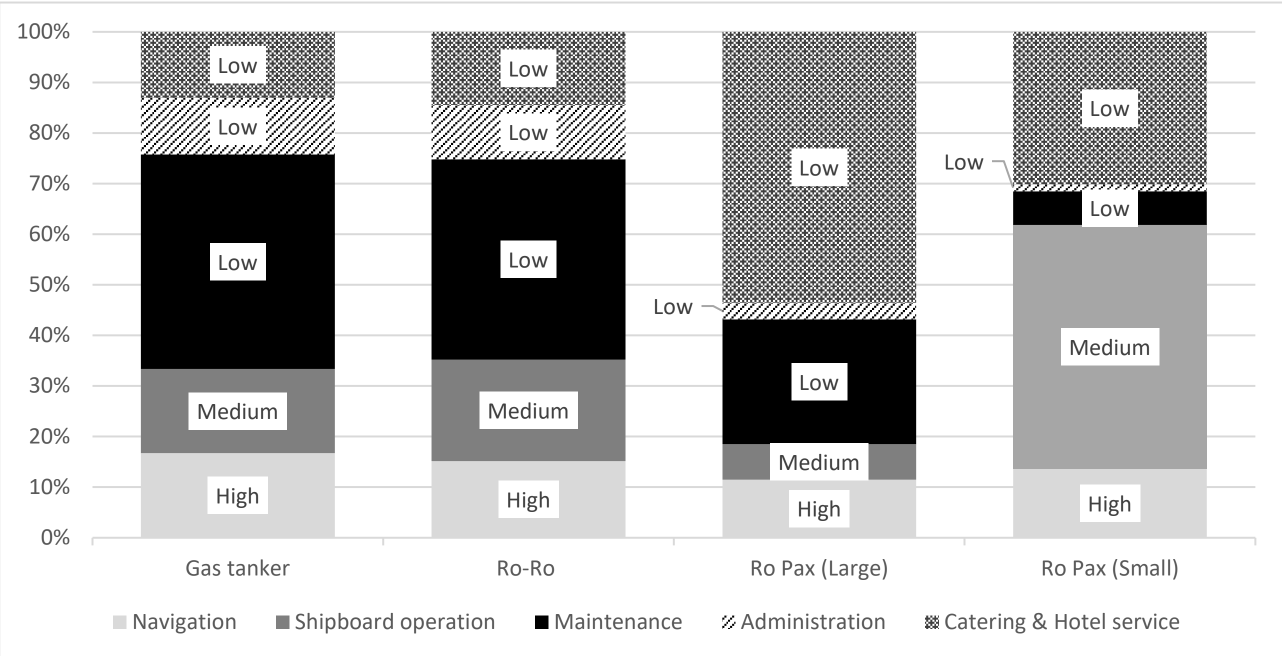

Figure 3 Distribution of work across analysed vessels, automation potential indicated

'Navigation' is remarkably similar across all four ships despite fundamental differences in type, size and operational pattern, making up between 12 and 17 per cent of the overall work burden. The two cargo ships, the gas tanker and the Ro-Ro, are very similar across all categories, even though these two ships are also very different. Not surprisingly, the 'Catering & hotel service' category constitutes a large part of the work time on both Ro pax vessels, but this is also the only similarity between the two. When ‘Catering & hotel service’ is excluded, the distribution of the remaining categories on the large Ro Pax closely resembles that of the two cargo ships. ‘Maintenance’ becomes the dominant category making up around half of the remaining work time in the three ships. The small Ro Pax really stands out from the three other ships, with only 7 per cent of the work time spent on ‘Maintenance’ and almost half spent on ‘Shipboard operation’. On the small Ro Pax, a total of 62 per cent of the work has a high or medium potential for automation compared to only 19 per cent on the large Ro Pax, 24 per cent on the gas tanker, and 25 per cent on the Ro-Ro.

The gas tanker and the Ro-Ro are very similar across all categories, suggesting that cargo ships are largely comparable in terms of work distribution, despite central differences in design, cargo type and operational pattern. When ‘Catering & hotel service’ is removed from the total workload, the work time distribution of the large Ro Pax closely resembles that of the two cargo ships even though the operational pattern of the small and large Ro Pax is almost identical. The size of the ships clearly has a stronger influence on the work time distribution of most categories than the operational pattern and ship type. Findings on the impact of automation on the workload, and by extension on labour costs, from studies of one size of ship, therefore, cannot be transferred directly to ships of different sizes.

It is concluded that the automation potential for ‘Navigation’ in isolation is high, but the overall workload cannot be significantly reduced if the focus is solely on automating tasks related to this category. When the automation of ‘Shipboard operation’ is considered, a significant part of the work on the small Ro Pax has the potential for automation, but the automation potential for most work tasks on the other three ships is still low. The fact that a task or category has the potential for automation does not mean that it is practical or economically feasible to do so. The automation potential, therefore, does not translate directly into reductions in workload and related costs. It is estimated that a realistic potential for reductions in the workload by automation across all four ship types in the analysis is in the range of 16 to 24 per cent. Overall, Paper VII finds that, while automation has a significant potential impact on the workload of small Ro Pax ferries, the potential impact of automation on the workload of larger cargo or passenger ships is limited.

7.4 Discussion - Workload & maintenance

Unlocking the full economic benefit of autonomous and/or unmanned operation relies on the work burden and as a result, the crew size and labour costs being reduced. Paper VI shows that legislation on safe manning is generally not a barrier to reductions in crew size for the large majority of ships. Papers V and VII show that both increased automation and unmanned operation can impact the workload required to operate modern merchant ships, but also that there are serious limitations to the magnitude of this impact.

Even though Paper VI clearly shows that the crew sizes of most ships, especially large ships, could be reduced significantly without violating the minimum safe manning, it does not mean that ship owners are free to replace any crew member with an automated system. Safe manning is not just a number, and crew members are not all the same. Fully automated navigation, for example, as has been the focus of much of the research and development within the area of autonomous ships, is not currently allowed under the existing maritime legislation (Danish Maritime Authority, 2017). A shipowner, therefore, cannot, for the present, choose to replace the navigating officers with an automated navigation system, should one be proven to be safe, reliable and commercially available. According to the interviewees in Paper VII, however, no such systems exist, and changes to the safe manning would not affect their actual manning. Shipowners or operators have a clear economic incentive to reduce the crew size, and, according to the interviewees, they would operate with smaller crews if they could. The interviewees point to the workload as the single limiting factor for reductions in the crew size. So why is the workload so high, and why are more tasks not automated?

Paper VII shows that modern merchant ships are, in fact, already highly automated and operating with severely reduced crew sizes compared to only a few decades ago. The automation revolution has already happened to a large extent (Hetherington et al., 2006), and it is perhaps not surprising that the tasks that remain are those found to be poorly suited for automation. In general, Paper VII does not find significant unexploited potential for automation. A notable and interesting outlier is ‘Navigation’, which is found to have considerable automation potential. ‘Navigation’ is, like other tasks onboard, already highly automated to the point where the bridge can be operated by just one person during sea passages. To further reduce the workload related to ‘Navigation’, the bridge would therefore have to be unmanned during some or all parts of the sea passage. So far, it has not been possible to reduce the bridge crew to less than one person, which has created a natural barrier towards further reductions in the workload in this category. The step from one person to unmanned is big, but developments in sensor and computer technology may now make it possible (Porathe et al., 2013). Because the bridge is only normally manned by one person, the effect of unmanned navigation on reductions in the total workload of operating the ship is, however, also quite limited, as Paper VII shows. Unmanned navigation, even only periodically, would be a revolutionary step in the operation of ships. As an enabler for totally unmanned operation of ships, however, the unmanned bridge is only a small step.

Besides the potential effects of automation on the reduction in workload, unmanned operation may in itself have an effect on the workload. As shown in Paper VII, without the need for an onboard crew, the ‘Catering & hotel service’ workload would not be needed on the two cargo ships. On the two Ro Pax most of the workload related to ‘Catering & hotel service’ involves providing services to the passengers and would not be greatly affected. Maintenance will also be affected by unmanned operation, as shown in Paper V. When increased redundancy is included, however, the overall effect of unmanned operation on the workload related to ‘Maintenance’ is negligible.

The automation potential identified in Paper VII cannot be translated directly into potential reductions in the workload. Paper VII estimates that a realistic potential for reductions in the workload by automation across all four ship types in the analysis to be in the range of 16 to 24 per cent. Unmanned operation may have an additional effect on the workload, but the extent to which at least parts of this workload 'disappear' is debatable. Work that is moved from the ship to shore must instead be done by people who also require workspaces, housing, food and drink, electrical energy, heating, air-conditioning, etc. From the local perspective, the work and resources needed to accommodate people may disappear from the ship, but in a global sense, much of it merely moves elsewhere. A reduction in the workload of 16 to 24 per cent is certainly significant and may be worth pursuing. However, the economic rationale of this depends on other costs related to automated and unmanned operation, such as more redundancy in equipment, more remote operation of equipment and more connectivity. The costs of labour and supplementary cost of accommodation at sea versus ashore will also be crucial. This balance will depend on many factors such as national and international policies, labour laws, tax structures, international economic inequality, etc.

8 RQ3: Operation & utilization

Unmanned and/or highly automated operation may potentially affect the operational patterns and the utilization rate of ships in both positive and negative ways. It may, for example, be necessary to extend harbour stays for unmanned ships at the expense of profit to accommodate for work that today is carried out by the onboard crew during sea passages. On the other hand, onboard crews also require access to provisions and crew changes that may interfere with the profitable cargo operation.

For large merchant ships, the workload related to maintenance is considerable, as shown in Paper VII, and as Paper V shows, this maintenance burden will remain largely unchanged for unmanned ships. When maintenance work cannot be done at sea because of unmanned operation, it must be done in port instead. Paper V investigates which effects the requirement for doing all the maintenance work in port will have on the operation of ships.

Besides the overall automation potential of work tasks, as described in Paper VII, the individual operation pattern of the four analysed ships may also affect the automation potential. Even though there are many similarities between the four analysed there are also critical differences that affect the possibility for highly automated and/or unmanned operation. Paper VII examines how the operational patterns and the different operational phases of the four analysed ships affect the automation potential.

Unmanned operation may bring with it specific issues regarding maintenance work as shown in Paper V, and automation may have its limitations, as shown in Paper VII. Manned operation, however, also imposes certain restrictions on the operation of ships. Ship crews require regular access to shore facilities for provisions, garbage disposal and crew changes, which may affect operational performance. Human error may also play a part in disrupting the operation of ships. Data on so-called off-hire events are introduced in this section to investigate the role of the crew in the interruption of the normal service.

This section addresses the research question of how unmanned operation and increased automation will affect merchant ships' operational patterns and utilization rate. A summary of the aspects of Papers V and VII that relate to this research question is given here. A brief analysis of data on off-hire events is presented, and research question 3 is discussed as a whole in section 8.4.

8.1 PAPER V

An overall summary of Paper V is given in section 7.1. Besides the findings presented in the overall summary, Paper V also investigates the viability of doing all the maintenance in port when ships are unmanned at sea. The total maintenance workload is found to be considerable at an average of 14,311 man-hours per ship per year, corresponding to 8.3 full-time positions. Based on operation data from the five ships in the analysis, as seen in Figure 4, it is found that the ships spend 14 per cent of the total time in operation in port. With changes to the work burden of only +/- 4 per cent resulting from unmanned operation, the work which must be done in this limited time is therefore considerable. In the fully unmanned case, it would require 10.8 people working around the clock at all times when the ship is in port to accomplish the total maintenance workload. This work only includes that which must be done physically on the ship, not the work that could be moved ashore.

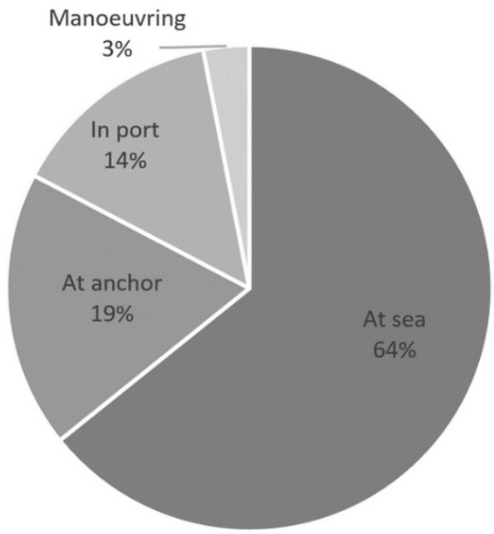

Figure 4 Operational mode distribution, Gas tankers

It is realistic to have 10.8 people working simultaneously on maintaining the ship. It would, however, require the ship to be maintained at every port of call. Many bulk and tanker terminals are situated in remote areas where such maintenance services might be difficult to sustain. If the ship is only to be maintained at every other port of call, for example, the number of people working on many different equipment units simultaneously might begin to be problematic. The calculated number of 10.8 people is also only a theoretical minimum because it would not be possible to utilize the entire time in port and plan work precisely to utilize the whole period. The duration of maintenance tasks may not be possible to predict with certainty in many cases. Care must be taken not to start tasks that cannot be completed before planned departure so as not to delay the operation. This issue is made worse by a large variety, and uncertainty of the length of port calls on many types of ships.

Besides doing maintenance in port as assumed in Paper V, it may also be possible to maintain ships while they are at anchor. Much of the crew change, delivery of stores, and bunkering occur at anchor today. However, the logistical challenges of getting maintenance personnel and equipment onboard a ship at anchor are greater than in port. Anchorages for large commercial ships are often miles from shore. If people are to work on the unmanned ship at anchor for extended periods, there must also be some form of rudimentary accommodation systems such as heating, air-conditioning, and toilet facilities on board, which would add to the maintenance burden. Alternatively, there could be a system of service/accommodation ships or platforms, perhaps in connection with a fleet of smaller crew transfer vessels, such as those used for offshore wind farms. This would, of course, also incur an additional cost on its own.

8.2 PAPER VII

An overall summary of Paper VII is given in section 7.3. Besides the findings presented in the overall summary, Paper VII also gives some indications as to where in the operation automation has the largest potential and how the vessel type, size, and operational pattern affects the potential for unmanned operation and increased automation. Some factors point toward cargo ships being the most suited for unmanned and/or a high degree of automated operation, while others point toward passenger ships being better suited.

Even though moving work tasks from ship to shore may not, in some cases, reduce the workload and the cost of the required labour, unmanned operation may still be an attractive option to pursue. As discussed in Paper I, many supplementary benefits can be realised if the ships can be made to operate fully unmanned. If there is no need for an accommodation the ship may be cheaper to build, they would be able to carry more cargo, and the energy consumption could be reduced because of minimised wind resistance and no electrical power demand to galley and hotel systems. In terms of reductions in workload, the need for ‘Catering & hotel service’ as identified in Paper VII would also no longer be needed. These supplementary benefits are, however, exclusive to the cargo ships. On the passenger vessels, these systems and most of the work relating to ‘Catering & hotel service’ would still be needed to accommodate the passengers.

Ferries have characteristics that make them suited to highly automated and/or unmanned operation in other ways. As explained in Paper VII, the operating pattern of the Ro Pax in the analysis is highly standardised with relatively short transits between the same two ports. The Ro Pax have dedicated berths and do not rely on external assistance for manoeuvring or mooring. There is much less variation in the operation of a Ro Pax than that of most cargo ships, which have a more complicated and varying operating pattern. The operation of the Ro Pax is more of a ‘routine task’ as identified in Paper VII as a positive indicator for automation. The small Ro Pax in the analysis is not in 24-hour operation but is stationary in port at night. This choice of operation is presumably based on consideration of costs versus benefits as there is nothing inherently preventing the ferry from operating continuously. If crew cost is less of a factor, it may be feasible to extend the operation.

On all four ships in the analysis, port operation is identified as a period of high workload and high work intensity. The operation of the two Ro Pax is optimised for short turnarounds in port, down to 15 minutes, in which they must unload and load all passengers and vehicles. For cargo ships, the port operations are longer but comprise a large variety of tasks typically involving all departments on board. Port operations are very time-critical and require ‘problem solving’, ‘situational adaptability’ and ‘social intelligence’, all negative automation indicators. This makes this operational phase a poor candidate for automation and/or unmanned operation.

Work within all five identified categories is done when the ships are in transit. However, except for ‘Catering & hotel service’, which would not be needed on the cargo ships if they could be made to operate unmanned, the only category that specifically must be done during transit is ‘Navigation’, which has the highest potential for automation. ‘Maintenance’ could, with all the reservations discussed in section 8.1, be done in port and ‘Administration’ could likely be done ashore, leaving only some tasks related to ‘Shipboard operation’, which may also be possible to automate. With the possible exception of when the ship is at anchor, transit is the operational phase best suited for automated and/or unmanned operation. There is nothing intrinsic in this phase, which makes unmanned operation impracticable besides the issues regarding redundancy and reliability as already described.

8.3 OFF-HIRE DATA

Human operation is deeply ingrained in today's conventionally manned ships. Modern merchant ships would not function without a crew, and no large, unmanned merchant ships are in operation today. A direct comparison between manned and unmanned operation, therefore, cannot be made. Isolating the role that the crew plays in the utilization of ships is not possible, but one parameter that can give an indication as to the extent to which the crew contributes to operational interruptions is the so-called off-hire data. An off-hire event occurs when the full working of the vessel is prevented, and the service of the vessel is therefore not available to the charterer (Falkanger et al., 2011). The shipowner or operator will not be paid by the charterer for the period in which the vessel is off-hire. A brief analysis of off-hire data is described in this section. This data has not found its place in any of the amended papers, nor has it been published elsewhere in this thesis. The off-hire data introduced here supplements the findings of Paper V and VII in the exploration of research question 3.

Utilization and operational efficiency of ships are of critical importance to shipowners, and extensive work has been carried out with the aim of optimising these aspects, see, e.g. Adland et al. (2018); Jia et al. (2019); Yang et al. (2020). This work primarily focuses on estimating or optimising either the utilization of the cargo capacity of ships, the cargo operations in port, or the ships' sea voyages. Most work has a business-oriented perspective or, as has become such an important in recent years, an environmental focus. No research has been found on the impact of ship crews on the utilization of ships. Neither has any research been found that specifically focuses on off-hire time.

The length and distribution of time off-hire is typically a closely guarded company secret, but one shipping company has made this data available for this thesis. Data are presented here in sufficient detail so the reader can understand the magnitudes of the off-hire categories, but the specific values are kept so general as not to reveal business-sensitive information. The identity of the company from which the data originated will also remain anonymous. The off-hire data originates from 29 ships over a period of 3.5 years between November 2015 and May 2019 and covers a total of 127 years of combined operation. Each off-hire event is attributed by the shipping company to one of the following categories:

- Crew non-compliance
- Insufficient oversight
- Manufacturer's fault
- Operational requirement
- Unavoidable random failure
- Planned maintenance, surveys and drydock

Planned and unplanned maintenance is the cause of the majority of off-hire events. Eighty per cent of the off-hire time is attributed to the following two categories: 'Unavoidable random failure' and 'Planned maintenance, surveys and drydock'. One category, 'Crew non-compliance', links the off-hire event directly to the actions of the crew. 'Insufficient oversight' and 'Operational requirement' could also, at least in part, be attributable to the crew. Each of these categories only makes up between one and three per cent of the total off-hire time. Out of the total time in operation, the time spent off-hire due to 'Crew non-compliance', 'Insufficient oversight', or 'Operational requirement' amounts to only 0.2 per cent. From the point of view of the shipowners or operators, the utilization rate of the ships is, in general, very high. The time spent off-hire constitutes a few per cent of the total time in operation. Out of these few per cent, only a very small proportion is caused by human error on the part of the crew. The presence of an onboard crew is clearly not the source of significant interruption to the operation of the ships.

8.4 Discussion - Operation & utilization

Modern cargo ships are massive structures capable of carrying enormous amounts of cargo. Huge sums of money are tied to ships and their cargo, so delays, operational stops, or operational inefficiencies can be very costly. Any improvement that autonomous and/or unmanned ships can potentially provide to the operational efficiency would drive the development of these forward. Any negative impact that autonomous and/or unmanned operation may have could be a serious barrier to their implementation.

Paper V finds that doing maintenance in port because of unmanned operation could be done without interfering with the operation. The intervals between planned maintenance jobs are typically longer than most voyages, and the duration of most maintenance jobs is shorter than typical port stays. Not all ports are equally well suited for maintenance, however. Small and remote ports may not have the critical mass of ship traffic to support a land-based maintenance service. The cost and quality of maintenance services from different contractors may also vary from port to port. Regardless of whether ship owners or operators wish to outsource the maintenance of their ships or keep it in-house, it would likely be desirable to concentrate the work on a few focused campaigns rather than having to do maintenance in every port. There is, however, a limit to how much work can be done during one port call, so maintenance must be done frequently if not to interfere with the operation of the ship. Not all work can be done during port calls either. Cargo and ballast systems can be difficult to maintain during loading and discharging operations in port. Oil, gas, and chemical tanker terminals are typically very restrictive regarding the type of work allowed during port operations. On ships such as the gas tanker analysed in Paper V, and many other ships in the tramp trade, maintenance may be done at anchor with the reservations mentioned in section 8.1. On ships such as the small Ro Pax analysed in Paper VII, which is not in continuous operation, maintenance may be done at night during off-service hours, as is already partially the case today. However, many ships inon a fixed-route schedule, such as the large Ro paxPax and the Ro-Ro analysed in Paper VII, are in continuous operation and do not spend any time at anchor under normal circumstances. It may not be possible for these ships to do maintenance only in port without interfering with the operation.

Operational efficiency may also improve with unmanned operation and/or increased automation. However, the potential for optimisation of the operation depends greatly on the perspective from which the operation is viewed. As the operational mode distribution in Figure 4 shows, the gas tankers forming the bases of the analysis in Paper V spend 19 per cent of the total operation time at anchor. Some of this time is used for tasks necessary to prepare for loading or discharging cargo, but a lot of it is spent waiting for the availability of a berth or for the cargo to be ready at the shore terminal. From the perspective of the charterer, much of this time at anchor is unproductive. The shipowner, however, is paid by the charterer for this time at anchor, so from the owner’s perspective, it is a productive and profitable part of the operation. From the shipowner's perspective, the operational efficiency is already very high, as indicated by the off-hire data in section 8.3. The ships are only off-hire for a very small proportion of the total time, and the large majority of this limited off-hire time is the result of planned and unplanned maintenance. Only an infinitesimally small proportion of the off-hire time is the direct result of the actions of the onboard crew.

The potential for optimising operational efficiency by autonomous operation of ships also depends on the perception of autonomy. The aspects of ship operation studied in this thesis, unmanned operation and increased automation of the ships, focus on the operation and capabilities of the ship. From a charterer or a global resource perspective, it may be desirable to minimise time at anchor, for example, but the capabilities of the ships are not really the limiting factor in this. Ships are instructed where to go, when to reach the destination, what to load, where to discharge the cargo and when and, as evidenced by the off-hire data, the ships very rarely fail to comply with these instructions. Shipping and chartering offices ashore know the position of the ships at all times, as well as their speed, destination, ETA to next port, cargo condition and a multitude of other information. Should any additional information be needed, the ships are continuously reachable by electronic communication. When autonomous ships are proposed as a means to ,optimise operations it is, for the most part, based on the broader, more conceptual understanding of autonomous ships as being part of an interconnected system as described in section 5.2. Significant operational gains could undoubtedly be achieved if a central system or operator had better knowledge of all ships, ports, terminals, and the rest of the intermodal transport chain. However, this is primarily a logistical issue, including many competing interests, which have very little to do with whether or not the ships are unmanned or highly automated. Autonomous ships in the conceptual understanding have a significant potential for improving operational efficiency. In the specific, definable, distinct understanding of autonomy as studied in this thesis, however, the potential is found to be very limited. This again underlines the importance of a common understanding of the nature of autonomous ships.

Reversing the focus and looking instead at how operational aspects affect the potential for unmanned operation and increased automation, some interesting trends have been identified. Differences are found along the lines of passenger versus cargo operation, small versus large ships, and fixed-route versus tramp trade. Cargo ships have more to gain from unmanned operation than passenger ships because the former would not need accommodation facilities, with all the potential befits such as lower build costs, less wind resistance, less energy consumption, etc. The maintenance burden would also be reduced, although only slightly, and the work related to ‘Catering & hotel service’ would no longer be needed on board. Smaller ships have smaller and simpler machinery systems, and the maintenance of this would be easier to do in port without interrupting the operation than on large ships. Ships operating on fixed routes have more standardised operating patterns, which are easier to automate than ships in the tramp trade. Ferries, which often have dedicated berths and highly automated mooring arrangements, are especially well suited to automated operation. The small ships studied in this thesis have almost exclusively been ferries. In Paper VI, five out of six ships on which the actual crew size did not exceed that required were small ferries. Paper VII also investigated a small ferry, but the paper finds that what distinguishes the small Ro Pax from the other three ships is not passenger operation but the ship’s size. The proportion of work time used in ‘Catering & hotel service’ was the only aspect found to connect the small Ro Pax and the large Ro Pax, which in all other aspects resembled the other two large cargo ships in the analysis. Passengers present unique challenges to unmanned operation that may be hard to overcome. The safety of passengers is critical, and large-scale unmanned passenger transport may be hard to legally accept (IMO, 2021b). Ferries on longer routes are also more than a mode of transport and often offer dining and leisure activities, which may be difficult to automate without losing revenue and customer satisfaction.

Looking across all the aspects of ship operation examined in this thesis, the ideal ship type for unmanned and automated operation would be small ships operating between dedicated and automated berths. Exciting projects aimed at automating the operation of small island or regional ferries, such as Rolls-Royce (2018a), have already been seen, but passenger safety is a very restrictive factor in regard to unmanned operation of ferries. Small cargo ships would be much better suited for unmanned operation, and it is perhaps not surprising that it is within this segment of ships where the most progressive unmanned and/or autonomous projects is seen, see, e.g. the Yara Birkeland (Yara, 2020) project and the ASKO autonomous ship project (Kongsberg, 2020). Small coastal or inland cargo ships are perceived and described by some as a proof of concept, a manageable first step and a steppingstone for widespread implementation of large autonomous and/unmanned ships in global trade (Jokioinen et al., 2016; Wariishi, 2019). As this thesis demonstrates, however, the crucial differences exist between small coastal ships on fixed routes and large ocean-going cargo ships exists, making the unmanned and/or highly automated operation of the latter a fundamentally different challenge.

9 CONCLUSIONS

This section presents the main conclusions of the seven appended papers presented in this thesis. Suggestions for further research are also given. For conclusions of the individual papers please see the appended papers in Part III.

This thesis examines autonomous merchant vessels from the perspective of operation and maintenance. Despite the broad interest in autonomy in the maritime domain, no unified definition or perception of the autonomous ship was found. Many definitions and perceptions exist, each has its application within different research areas, but none are yet universally accepted across research fields. Because of this uncertainty, the focus of this thesis has been on tangible aspects of ship operation, which are often, but not always, associated with autonomous ships: namely increased automation and unmanned operation.

9.1 RQ1: HOW WILL UNMANNED OPERATION AND INCREASED AUTOMATION AFFECT THE RELIABILITY AND NEED FOR REDUNDANCY OF MERCHANT SHIPS?

Reliability of machinery equipment is found to be a serious barrier to unmanned operation. In agreement with other studies on the subject, it is found that more redundancy of machinery equipment will be needed on unmanned ships. The use of the Reliability Centered Maintenance (RCM) method as a tool for evaluating maintenance and reliability needs on unmanned ships is evaluated, and amendments to the method are proposed. While the reliability of machinery systems is not found to be markedly higher on an unmanned than on a manned ship, the consequences of failures are found to be much more severe because of the severely restricted possibilities for doing corrective maintenance when at sea. To maintain an equivalent level of risk, the probability of failure must therefore be lower on unmanned ships. Redundancy can reduce the probability of failure in systems consisting of otherwise fairly unreliable equipment units, but redundancy also has its own limits. Redundancy can reduce the probability of independent failures to infinitesimally small values but will generally not have any effect on dependent failures. The effect of redundancy is therefore effectively limited by the probability of dependent failures. Increased redundancy can also have negative effects on the reliability of ship systems as more equipment also adds to the possible interactions between systems, the consequences of which can be very difficult to predict. At some point, adding more redundancy will not increase reliability any further but only serve to increase the complexity of systems. The inherently uncertain nature of failures, the limited effect of redundancy, and the severely restricted possibilities for corrective maintenance make reliability a very serious obstacle for unmanned ships.

9.2 RQ2: HOW WILL UNMANNED OPERATION AND INCREASED AUTOMATION AFFECT THE WORKLOAD REQUIRED FOR OPERATING AND MAINTAINING MERCHANT SHIPS?

Much of the economic benefit of autonomous and/or unmanned operation of ships is projected to come from reductions in crew costs. There may be benefits to moving certain jobs ashore, but for labour cost reductions to be fully realised, the workload related to the operation of the ships must be reduced. Unmanned operation is currently prohibited by maritime legislation, but drastic reductions in crew size are not found to be restricted by the minimum safe manning for the majority of ships. The single limiting factor in further reductions in crew size is found to be the workload. Shipowners have a clear economic incentive to reduce the crew size, and they can legally do so, but the technical systems needed to make this possible are lacking. The largest potential for automation is found in the work related to navigation, but it is also found that navigation-related work only comprises a smaller part of the total workload. Automating the navigation would be a radical step in the operation of ships, but most of the workload would remain unaffected by this. The largest overall automation potential is found in small vessels. For larger ships, the automation potential is found to be much more limited. Overall, it is not found that there is a large unexploited potential for automation on merchant ships. Maintenance, which is not well suited to automation, is found to make up a considerable part of the total workload on large ships. The maintenance-related workload is not found to be affected significantly by unmanned operation.

9.3 RQ3: How will unmanned operation and increased automation affect the operational patterns and utilization rate of merchant ships?

Commercial shipping is a very competitive business, and ships must be in near-constant operation to generate profit. Any positive contribution to the operation that autonomous operation could provide would propel the concept of autonomy in merchant shipping, – and any negative impact would be a serious barrier. Doing maintenance in port on unmanned ships is found to be practically possible, but it would require ships to be maintained in almost every port, as there is a limit to how much work can be done simultaneously. Other operational parameters may prevent some maintenance tasks from being done in port but may also open up the possibility of doing maintenance at anchor for some ships. Shore-based maintenance is not an impregnable barrier for unmanned shipping, but it is a major challenge. The potential for autonomous operation of ships for optimising the operation is found to depend greatly on the perspective of the operation of the ship and on the perspective of autonomy. From the ship owner's perspective, the operational efficiency is found to be very high, and the inoperable time attributable to the crew is extremely limited. From the perspective of the charterer, the potential for automation is larger, but neither the crew nor the automation level of the ship, however, are found to be the limiting factors. In the more conceptual perspective of autonomous ships as being part of an interconnected system there may be significant potential for operational optimisation. Unmanned operation and increased automation of ships as studied in this thesis, however, are not found to have significant potential for improving the operational efficiency. Differences in the potential for automation and unmanned operation are found along the lines of passenger versus cargo operation, small versus large ships, and fixed-route versus tramp trade. These differences mean that solutions found for one type of ship or research done within one type of operation cannot be directly transferred to another. The challenges of unmanned and/or highly automated operation are very different for small coastal ships on fixed routes, for example, than they are for large, ocean-going ships in tramp trade.

9.4 SUGGESTIONS FOR FURTHER RESEARCH

In the course of researching and writing the present thesis, additional areas of research that have not been fully explored and that should be further examined have been identified. Some suggestions for future research are given here.

- More research is needed on the effects of increased redundancy on maintenance. The assumptions made in Paper V are believed to be of sufficient accuracy of the specific analysis, but knowledge is lacking on the specific effects of redundancy in equipment on the maintenance workload. A standby system with two pumps, for example, would require more maintenance than a system with a standalone pump, but probably not twice as much. Equipment units at standstill will still experience degradation and will require maintenance even if they are not running, but equipment in use will experience more wear.
- The effects of condition monitoring and predictive maintenance on reliability and maintenance should be further explored. Condition monitoring and predictive maintenance can be used to avoid approaching failures, thereby improving reliability, or to extend the useful life of components, thereby reducing maintenance. These effects, however, are difficult to quantify and should be explored in more detail.
- Unmanned operation of ships may require increased use of condition monitoring and predictive maintenance, but there is a cost related to this. Small equipment units are typically not afforded the same measurement and monitoring equipment because the costs of sensors may exceed the cost of failure of the equipment. A method for reliably evaluating the costs versus benefits of condition monitoring and predictive maintenance under different conditions, such as unmanned operation, is needed.
- Condition monitoring and predictive maintenance are better suited to some equipment units, components, or types of failures than others. Unmanned and/or autonomous ships may require more condition monitoring and predictive maintenance, but there may also be failures where this is not practically feasible. The extent to which failures that occur on today’s conventional ships could be predicted and prevented should be studied in more detail.
- Unmanned and/or autonomous operation of ships will, according to some, shift the balance in favour of smaller ships because the eliminated or reduced crew costs will diminish the economy of scale of large ships. Economy-of-scale, however, also works on fuel efficiency and build and operational costs. How these different factors individually affect the economic differences between small and large ships should be further investigated.

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PART III
Appended Papers

Paper I

Eriksen, S*.* **Autonomous Ships – Changing Perceptions and Expectations,** *Proceedings of the 18th Conference on Computer and IT Applications in the Maritime Industries, Tullamore, Ireland, 2019*

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Autonomous Ships – Changing Perceptions and Expectations

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Abstract

This paper investigates the perception of what autonomous ships are and whether this perception has changed over time. Research project material, scientific material and news articles on autonomous ships are analysed to investigate how the concept of the autonomous ship and its benefits are perceived. Some common understanding is found, but also considerable uncertainty as to whether autonomous operation implies unmanned operation. In the scientific material, a tendency to clearly distinguish between the autonomous and unmanned is becoming more prevalent. The implications of this ambiguity in relation to the expected benefits of the autonomous ship are discussed.

1. Introduction

Automation has been used on ships since probably before the introduction of the steam engine. Technological innovations allow tasks previously carried out manually to be automated, enabling fewer crew members to operate ever larger and more complicated vessels, safer and with greater efficiency. With technology advancing faster than ever, it is a small mental leap to extrapolate this evolution to a scenario where automation takes over completely, and crew members become obsolete all together. This idea of the fully automated and unmanned ship is nothing new, rather it has been around for at least 30 years, *Bertram (2003*). In the 1980s, it was called the intelligent ship, see e.g. *Noma (2016),* but it is now often referred to as the autonomous ship. While the concept of the fully automated, or at least highly automated, ship is not new, using the term autonomous to describe the ship is relatively recent. The term "autonomous ship navigation" was used as early as 1991, *Stamenkovich (1991),* but the earliest instance of autonomous being used to describe the vessel as an entity found in the literature search for this paper was an article from 2004, *Young-il (2004)*. Autonomy is proclaimed as a disruptive technology with the potential to revolutionise the maritime transport business, *Jokioinen et al. (2016),* and autonomous ships have become an important research topic. Despite the interest in the topic, there is considerable uncertainty regarding what actually constitutes an autonomous ship, *Pico (2017)*. Much work has been done to define the term. IMO has begun work to define the autonomous ship within their regulatory framework, *IMO (2019)*. Lloyds Register and other classification societies have described autonomy levels that can be assigned to ships, *Lloyd's Register (2016)*. Academic work has also been done on defining the autonomous ship, including *Rødseth and Nordahl (2017)* in "Definitions for Autonomous Merchant Ships".

The Oxford lexical definition of autonomy as "the ability to act and make decisions without being controlled by anyone else", *Hornby et al. (2005),* may not at first glance appear very different from the common perception of autonomy in shipping. To "act and make decisions", however, implies the ability of an entity to generate desire and act on that desire as opposed to acting on the desires of the creator, *Intel (2018)*. A truly autonomous system would act on its own laws and objectives and thus be inherently un-deterministic. In the words of Rødseth and Burmeister *(2012),* "the more autonomy that is assigned to a robot, the less controllable it is. The ultimate autonomous robot is the fully intelligent robot which in principle is not controllable at all, except by very high level objectives." Such a system is obviously not desirable and quite far from even the most futuristic versions of the autonomous ship.

The word autonomy has clearly come to mean something else in the general discussion of autonomous ships. This is not in itself a problem: words change meaning or are used in different contexts all the time. For example, if an object was said to be artificial in the 14^{th} century, this meant that it was artfully created by someone with great skill *@listverse (2016)*. The problem arises when the new use of the word is not clearly defined or if there are conflicting definitions, perceptions and uses. An unclear definition is problematic since a statement or projection may lead to unrealistic expectations if the reader's understanding of the term does not match that of the author. It may on the other hand also lead the reader to conclude that the author is making unsubstantiated claims. Ambiguity in the term also makes it hard to challenge statements made by authors if exact definitions are not stated in every case.

The focus of this article is not to question the existing definitions of autonomy or the autonomous ship. Instead, it will explore how the autonomous ship is perceived and defined by those working with the concept. Research projects, scientific literature and maritime news sources are analysed to determine what characterises the autonomous ship in the broader maritime community as well as if and to what extent there is agreement on this perception. Perceived benefits of the autonomous ship and the expected challenges in its development are also collected from the three different sources and analysed.

2. Autonomy versus automation

Automation is the use of machines or computers instead of people to do a job, *Cambridge Dictionary (2019)*. We are surrounded by automation in our daily lives, from the simplest mechanical radiator thermostats to the complex algorithms running internet search engines. The terms automation and autonomy certainly sound similar but, while a refrigerator is able to maintain a stable temperature without human interaction, most would agree that a refrigerator is not an autonomous system, even if the definition of the word may have changed. Autonomy and automation are two different things, but they certainly overlap. Both can be described as existing on a scale with manual operation on one end and autonomy or automation respectively on the other. An autonomous system within the realm of technology must surely require a high level of automation. The question is: if the level or complexity of automation is in itself enough to make a system autonomous and where in that case the dividing line is.

Modern ships have an enormous amount of automation on board without being what is commonly considered autonomous. Most systems are standalone systems designed to automate a single piece of equipment such as a boiler, purifier or automatic filter. Some systems are connected together in groups or even into one integrated control system encompassing many different subsystems. On many ships, generators are started and stopped without any human interaction on signals given by the power management system, for example. Engine control systems are becoming increasingly more complex, regulating fuel injection and valve opening timing within milliseconds for the purpose of optimising fuel efficiency and exhaust gas quality.

The same engine control systems have existed in cars for many years, making these vehicles highly automated but still no nearer to autonomous. In the automotive world, the term autonomous suffers the same issue of not really meaning autonomy any more. In the words of one Nissan engineer, “a truly autonomous car would be one where you request it to take you to work and it decides to go to the beach instead,” *Autotrader (2019).* The common understanding is that the term autonomous car refers to one where the driving is automated. This idea also seems to apply to ships, but the issue of self-driving gets a little more complicated here. The autopilot controls the ship’s heading for most of the ship’s voyage under constant monitoring by the navigating officer. Even simpler autopilots now offer the feature of following a track as laid out on the electronic chart and automatically changing course at waypoints. Of course, the autopilot only normally controls the rudder and not the machinery or thrusters. Ships with Dynamic Positioning (DP) systems go further than this and are able to maintain a stationary position and even carry out planned manoeuvres with great precision totally independent of human interaction. None of these systems, however, are able to “look” out of the window, perceive other ships and avoid collisions based on those inputs.

If self-driving is the dividing line between autonomous and non-autonomous, then the only missing piece is the ability to detect and avoid other ships or objects in accordance with the International Regulations for Preventing Collision at Sea (COLREGS). If unmanned operation is, however, part of what defines an autonomous ship, then self-driving is only part of the puzzle. After all, it must be remembered that, unlike in road transport, driving the vessel is just a small portion of the work carried out on board large cargo ships. Autonomy, as already mentioned, is sometimes described as being on a scale. One commonly used scale is Lloyd’s autonomy levels that ranges from AL 0, “Manual – no autonomous functions” to AL 6 “Fully autonomous”, *Lloyd's Register (2016)*. The problem presented by these scales, in the context of understanding what defines an autonomous ship, is that all ships no matter how primitive essentially fall into the spectrum and could be designated as autonomous in some form.

Where does that leave us in the understanding of the autonomous ship? In summary, the definition of autonomy found in the dictionary is not what is meant by autonomy in shipping. Automation is crucial for vessel autonomy, but the level or complexity of automation may not in itself be what enables autonomy. Self-driving may be a crucial ability, but if unmanned operation is part of the perception of autonomy, then this is only part of the solution.

3. Methodology and data collection

The basis of this article is literature on the subject of autonomous surface ships, with particular emphasis on merchant vessels. The sources can be divided into three categories: research projects as discussed in section 3.2, scientific literature and news articles both discussed in section 3.3. The material used has been gathered through an exploratory literature search. As much literature from the research projects that could be found and publicly accessed has been used. Regarding scientific literature and news articles, a volume has been found, selected and used that is believed to constitute a representative part of the total available material. In neither of the categories does the list of materials claim to be exhaustive.

3.1. Methodology

The material for this article was read and analysed with the purpose of investigating how the texts discuss the concept of autonomous ships. The focus is on how words or phrases are used in the texts and how they describe the subject in general. The material was processed with a focus on how a knowledgeable reader would understand the text. Understanding a text, however, is highly subjective and different readers will form different understandings of the texts based on their specific knowledge, attitude and focus. Effort has been put into not extrapolating or interpreting statements and not reading preconceived understandings into the text beyond what the author intended. The material was largely read and analysed by the same person. Selected material has been analysed by more than one person to validate the method and results.

3.2. Research projects

The available material was studied and analysed with a focus on the following categories:

- How is autonomy defined, and what characterises the autonomous ship?
- How is the term automation used in relation to autonomy?
- What are the expected benefits of the autonomous ship?
- What are the expected challenges in developing and operating the autonomous ship?

The analysis of the projects is presented in sections 4.1 and 4.2. In the category of autonomous and/or unmanned ships, two projects stand out: "Maritime Unmanned Navigation through Intelligence in Networks", MUNIN *(2018),* and "Advanced Autonomous Waterborne Applications", AAWA *(2016).* Other commercial projects exist, most notably the Yara Birkeland project, *Kongsberg (2019),* but also the planned NYK *(2019)* test of an autonomous container vessel. The publicly available material on these projects is, however, very limited. The material published by MUNIN and AAWA provides the most comprehensive project descriptions available and is also referenced frequently in other sources. The two projects are briefly described in the following.

3.2.1 MUNIN

The MUNIN project, *MUNIN (2018),* was a three-year collaborative research project that completed its work in 2016. The project was mainly funded by the European Commission under its Seventh

Framework Programme. There were eight partners in the project, consisting of educational institutions, private research institutions and technology companies.

3.2.2 AAWA

The AAWA initiative was led by Rolls-Royce and ended in 2017, *Jokioinen et al. (2016)*. The project was funded by the "Finnish Funding Agency for Technology and Innovation". Contributors to the project included several of Finland's largest universities as well as industry partners such as DNV-GL and Inmarsat.

3.3. Scientific literature and news articles

The literature included in this paper comprises articles published in scientific journals and articles from conference proceedings including five from previous COMPIT conferences. One working paper is also included. Articles and presentations from the MUNIN and AAWA projects are discussed under the research projects category. The focus of processing scientific literature in this paper is on understanding how researchers not associated with these projects perceive the concept of autonomous ships. Material with different focuses, such as legal, business, technological and human nature aspects, have been included to get as broad a view of the perception of autonomous ships as possible. In all, twelve scientific papers were analysed.

News coverage should not be treated as an accurate source of scientific material, but news articles are included in this article as they convey how the concept of the autonomous ship is perceived by the public. To the reader with a cursory interest in the subject, maritime and business-oriented news sources are likely to be their main source of information. How the definition, benefits and prospects of autonomous ships are portrayed in the news is likely to form the perception of the subject in the broader public. The news articles mostly originate from open source online magazines. One press release is also included in this category. The search was conducted as one normally would if looking for news on autonomous ships online, through searching well-known online maritime news sites, such as worldmaritimenews.com and shippingwatch.com, and through generic web search engines.

A quantitative approach was adopted in the analysis of both scientific literature and news articles. One matrix for the scientific literature and one for the news articles, as seen in tables I and II, were constructed with categories based on what was found in the research project analysis. The matrixes in tables I and II are similar but not identical. Some terms or statements are prevalent in the scientific literature but not in the news articles and vice versa.

Date of publication is noted, and for the news articles also which sources are quoted. The use of the term autonomy versus automation and unmanned versus autonomous is assessed to determine if there is a "clear separation" or "no or unclear separation" between the terms. "No or unclear separation" means that the terms are explicitly used synonymously, or the connection is clearly implied such as "[…] a challenge for an autonomous vessel designed to operate safely without any crew onboard", *Willumsen (2018)*.

The analysis treats the article or paper as one collective piece but allows for conflicting statements in the text. If one source refers to a benefit of autonomous vessels, for example, while another source, the journalist or the author presents an opposing statement, both views are registered for that article. If a benefit is only mentioned for the purpose of opposing it, only the opposing view is recorded. The same is the case for relationships between statements. In one news article, two sources are interviewed that each has their own take on autonomy. The first source explains "[…] there are many perceptions of what "autonomous" actually means and whether the term refers to unmanned or manned vessels", *Pico (2017)*, separating the two terms. Later in the article, the other source states that "in general if we compare manned and autonomous vessels, the savings for autonomous vessels is roughly 23 percent […]", clearly implying that the autonomous vessel is unmanned. In this case, both categories "no or unclear separation" and "clear separation" are registered.

4. Analysis

4.1. MUNIN

The material studied in this analysis consists of twelve papers, eleven deliverable reports and four brochures completed by twenty-two different authors or editors. All the material is available on MUNIN's website *(2018)*.

4.1.1. MUNIN's perception of the autonomous ship

MUNIN investigated potential concepts for partially and fully unmanned ships by exploring the specific case of a bulk carrier in intercontinental trade. The focus was on unmanned operation, but the vessel was intended to operate autonomously or automatically for large parts of the voyage. When operating close to land, the ship was either to be controlled remotely or operated by an onboard crew. The vessel must be able to call for assistance by remote control in situations where the onboard control systems cannot cope. If a connection to land cannot be established, the vessel must enter a fail to safe mode, which could mean maintaining a stationary position, essentially requiring a dynamic positioning system, *Rødseth and Burmeister (2012)*. The ship must have a large degree of mechanical redundancy and would require more advanced automation and more sensors than conventional ships.

The MUNIN project was initiated by the Waterborne TP, which defines the autonomous ship in its "Strategic Research Agenda" *(2011)* as a vessel incorporating: "next generation modular control systems and communications technology [that] will enable wireless monitoring and control functions both on and off board. These will include advanced decision support systems to provide a capability to operate ships remotely under semi or fully autonomous control."

The article "Developments Towards the Unmanned Ship" by *Rødseth and Burmeister (2012)* sets out the initial position and rationale regarding the development of an unmanned ship within MUNIN. In the article, the relationships between the terms automatic, autonomous, and intelligent control are discussed. It is explained that full autonomy as defined by Waterborne TP is not desirable within the MUNIN project since such a system with no constraints would be non-deterministic and "[…] it cannot a priori fully know what the possible outcomes of the decision will be." This level of autonomy, which Waterborne TP calls fully autonomous, is described as intelligent within MUNIN. Somewhat confusingly, intelligent comprises an autonomy level above autonomous as seen in fig. 1. Automatic is below autonomous on the scale of autonomy.

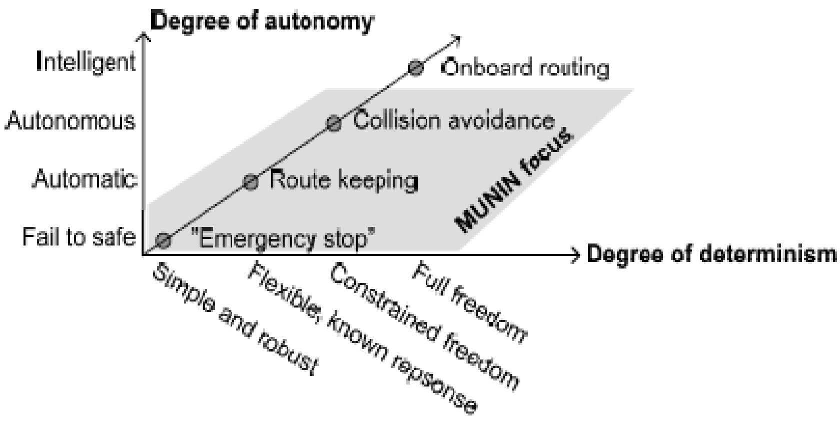

Fig 1: Autonomy versus determinism in MUNIN, *Rødseth and Burmeister (2012)*

Within MUNIN, autonomous control is defined as "the ability to make complex decisions that may not be easily described through mathematical or logic formulas, but which still are constrained within certain predefined limits", *Rødseth and Burmeister (2012)*. The authors explain that "most systems that claim to have autonomous control functions […] are mostly automatic rather than truly autonomous or even intelligent" and goes on to explain that "MUNIN will develop the principles for a basically automatic ship, but with some capability to handle certain unplanned situations within defined constraints."

4.1.2. Autonomy versus automation in MUNIN

As seen from the statement in section 4.1.1., what is meant by autonomy in MUNIN is to a large extend an advanced form of automation. This is supported by fig. 1, where autonomy and automation are presented on the same scale.

The term automation is used infrequently in the material. When it is, the notion that automation will lead to autonomy is mostly supported, such as here: "it is assumed that gradual automation will step by step lead the way from today's conventional shipping to truly autonomous shipping in the future". In other places, it appears that automation in itself will not lead to autonomy, such as: "as there is normally no crew aboard during autonomous operation, the unmanned vessel not only has to be equipped with high fidelity automation and various additional sensor systems, it also needs facilities for autonomous operation", *Kretschmann et al. (2015)*.

4.1.3. Autonomy versus unmanned in MUNIN

In one of the project's earlier publications, the terms autonomous ship and unmanned ship are defined in the contexts of MUNIN: "An autonomous ship is navigating and making evasive maneuvers based on an automated software system. The system and the ship are under constant monitoring by a Shore Control Center (SCC). An autonomous ship does not have to be unmanned but can contain maintenance or service crews, while the bridge and/or the engine control room is unmanned. An unmanned ship is a ship with no humans onboard. An unmanned ship does not have to be autonomous; it can be under autonomous control but it can also be under remote control from a SCC, or from other places (e.g. a pilot or tug boat, or a mooring supervisor)", *Porathe et al. (2013).*

This definition clearly separates the two terms: an autonomous ship can be manned, and an unmanned ship is not necessarily autonomous. Despite this clear separation, the two terms are often used interchangeably and sometimes synonymously throughout the material. Some examples: "obviously with the autonomous vessel there is no Master and crew on board."; "it is not considered that the liability risks of the autonomous ship will differ greatly from the manned ship save for the obvious exception of there being an eliminated risk of personal injury/illness and death of crew", *Kretschmann et al. (2015).*

Use of the terms unmanned and autonomous varies greatly throughout the different publications, which sometimes favour one term or the other but often use a mix of the two interchangeably. Unmanned is used both to describe the vessel as an entity and the operation of the vessel. Autonomous is used to describe the ship as an entity, its mode of operation or navigation as well as the bridge and engine room systems controlling the autonomous ship.

A detailed analysis of where the terms unmanned and autonomous are used has not been carried out but unmanned tends to be used more in sections discussing legal issues, for example, while autonomous is used more frequently in parts where control systems are described. It is also possible that the different authors favour one term over the other in different contexts.

4.1.4. Benefits and challenges of autonomous ships in MUNIN

The main benefit of the autonomous ship expected in the MUNIN project is a reduction in crew costs. Improved safety of both the ship and people due to a reduced risk of human error is also an important advantage. Human error is the cause or a contributing factor in the majority of marine accidents, *Allianz (2017)*. Autonomy is expected to improve ship safety by replacing the human operator with automation. By eliminating the crew, the risk of harm to people on board also disappears. The risk of fire onboard or pollution from the ship is also expected to be reduced since it will be possible to fill enclosed spaces with inert gas without having to consider the safety of a crew.

Regarding operational factors, MUNIN explains that autonomous operation would promote slow steaming and reduce off-hire time. The vessel's construction could be optimised if there were no need to house a crew. There would be no need for an accommodation, which would reduce the weight of the ship, reduce wind resistance and leave room for more cargo. Hotel systems for the crew, such as sewage and air conditioning, could also be eliminated. This would make the ship simpler and more reliable. Eliminating the accommodation and hotel systems would also reduce the building cost of the ship as wells as the fuel consumption and therefore also the emissions. MUNIN also considers it necessary to run the engines on diesel instead of heavy fuel oil, which would simplify the fuel oil system, making it cheaper and more reliable.

Ship intelligence is what MUNIN calls the benefits originating from increased data collection and processing. Increasing the intelligence of the ship is expected to optimise operation, route planning and weather routing as well as allowing for better condition monitoring and management of machinery. MUNIN's main focus is on unmanned operation and it explains that the benefits originating from ship intelligence are not exclusive to unmanned ships. Traditionally manned ships or vessels with reduced manning could incorporate these technologies and reap the benefits of increased ship intelligence.

The challenges in developing and operating autonomous ships as perceived within MUNIN are achieving sufficient technical robustness, breakdown of non-redundant machinery and communication link failure. Also mentioned is the difficulty of participating in rescue operations and interacting with conventional ships in general. The lack of legal and contractual frameworks around autonomous ships is also mentioned. Autonomous ships may need longer port stays to allow time for maintenance. Regarding human factors, the difficulty of transferring "ship sense" to the control centre is mentioned along with the issue of automation awareness where the operator is not fully conscious of what the automated system is doing.

4.2. AAWA

This analysis is based on the document entitled "AAWA Whitepaper" or "Remote and Autonomous Ships – The next steps" published in 2016 by *Jokioinen et al. (2016)*. The document spans 84 pages and is a collaboration between 16 authors.

4.2.1. AAWA's vision of the autonomous ship

The object of AAWA's research is not a specific concept of one type of ship but rather the development of remote and autonomous ships in general. Some general prerequisites are, however, mentioned for a ship to safely operate autonomously. The autonomous ship must be under constant supervision from a shore control centre that is alerted and able to take over control if a situation that the onboard system cannot cope with is encountered. If the connection is lost and the onboard system is not able to resolve a situation, the ship must be able to proceed to a safe location and maintain its position, essentially requiring dynamic positioning capabilities. More mechanical redundancy is required, along with more advanced automation and more sensors.

Autonomy, or the autonomous ship, is not explicitly defined in the AAWA material. Autonomous is generally used to describe the ship as an entity but the term is also used synonymously or interchangeably with smart and intelligent. "Autonomous shipping is the future of the maritime industry. As disruptive as the smart phone, the smart ship will revolutionise the landscape of ship design and operations." Mikael Makinen, President Rolls-Royce Marine, *Jokioinen et al. (2016)*. "Two years ago talk of intelligent ships was considered by many as a futuristic fantasy. Today, the prospect of a remote controlled ship in commercial use by the end of the decade is a reality".

4.2.2. Autonomy versus automation in AAWA

Automation is not frequently used as a term in the material. When it is used, it generally supports the notion that automation leads to autonomy. "From a technology point of view, autonomous vessels and self-driving cars may have many things in common[…] For example, ships are more likely to be operated by companies than by private individuals and automation is more focused on remote control than complete automation, at least in the early phases”; “safety and security impose essential constraining requirements that need to be fulfilled in the design and implementation of ship automation. In principle, autonomous or tele-operated ships are required to be, at least, as safe as conventional vessels in similar service”, *Jokioinen et al. (2016).*

4.2.3. Autonomy versus unmanned in AAWA

The object of the AAWA project is the autonomous ship but in the context of AAWA in general this is an unmanned ship. Many of the benefits of autonomous ships proposed in the material originate from there being no crew on board. Autonomous vessels are also juxtaposed with manned vessels in the text, such as here: “however, there will always be manned vessels sailing along with autonomous ships”. Autonomous vessels are also referred to as having no crew on board: “autonomous ships involve greater legal challenges than remotely operated ones. The latter ones still have a crew, even if not on board […]”; “lack of permanent crew on-board the autonomous ships would emphasise the role of port operators in accepting the cargo […]”. In a few places in the text, the autonomous ship is discussed as having a crew: “the crew members need to be trained in any case to fulfil all functional tasks and capabilities left for the crew in autonomous ships,” *Jokioinen et al. (2016).*

Autonomous is generally used more frequently than unmanned but use of the two terms varies greatly throughout the text. Autonomous is used almost exclusively to describe the ship as an entity except in the chapter discussing legal issues, where unmanned is mostly used.

4.2.4. Benefits and challenges of autonomous ships in AAWA

Many of the same benefits and challenges mentioned in MUNIN are also proposed in the AAWA project. AAWA also considers the main benefits to be reduced crew costs and improved safety for the ship and people due to the elimination of human error. No accommodation and hotel systems with all the resulting benefits is also frequently mentioned. Building and operational costs are expected to fall, while productivity, reliability and eco-efficiency are expected to improve.

More data is expected to optimise the ship's operation, enable more effective pooling for the shipping operator, open the door to new leasing opportunities and allow for better online cargo services. It is also expected to optimise route planning and weather routing as well as allowing machine diagnostics, improving the maintenance schedule and enabling the ship owner to obtain a better fuel price.

The challenges in developing and operating autonomous ships as perceived within AAWA are a shortage of internet bandwidth, the dangers of hacking, signal latency in remote operation, difficulties in obtaining satisfactory fusion between sensors and conflicting sensor data in general. There is also the danger of skill degradation in operators, since they may not get sufficient experience if the autonomous system is in control most of the time. Skill degradation, combined with reduced situational awareness, is reported as especially critical when operators are required to take over control at short notice in emergency situations. Poor situational awareness and poor automation awareness also pose a risk especially when the operator is expected to monitor multiple ships. It is expected to be difficult to incorporate the concept of “good seamanship” into an autonomous system, making it a challenge to comply with COLREGs. The fact that existing legislation and contracts do not accommodate autonomous ships is also mentioned. AAWA also believes the risk of cargo-related incidents may rise.

4.3. Scientific papers

The scientific papers covered in this article focus on different aspects of autonomous ships, such as legal, commercial and human aspects, or on the development or testing of specific technical systems. How precisely the concept of the autonomous ship is defined varies depending on the focus of the article. Papers that explore the broader implications of the introduction of autonomous ships, for example, tend to be very specific in their definition. Articles that describe technical systems tend to describe the system and how it was developed or tested in great detail, while the general concept of ship autonomy tends to be only vaguely defined if at all, since it is not important for the understanding of the system described. The scientific papers used in this article are considered to be of a high quality and the analysis is not an assessment of this in any way. Nor should the analysis be taken as a comment on whether the concept of the autonomous ship is considered to be adequately defined or not. The analysis serves only to investigate how the papers present the concept of the autonomous ship within their own frameworks.

Automation is very rarely used as a term in the scientific material in general and only in one article is it used synonymously with autonomy. The term smart is used as either an overarching term that encompasses the autonomous ship or synonymously with autonomous in three articles.

In four articles, there is a clear separation between the terms autonomous and unmanned. One example: "note that the terms unmanned and autonomous ships are often interchanged, but they are not the same. An unmanned vessel could be remotely operated, and it's therefore not autonomous; while an autonomous ship could be manned", *Mediavilla et al. (2016)*. In six articles, there is no or unclear separation between the terms, such as here, where manned and autonomous are juxtaposed: "future work will deal with: conflicting rules, interaction of autonomous and manned vessels […]", *Mediavilla et al. (2017)*. Sometimes, the two terms are used interchangeably: "it is established that not all commercial goods will be suitable for autonomous transport by sea. Unmanned vessels are expected to carry cargoes that are stable and non-hazardous," *Hogg and Ghosh (2016)*. In other cases, it is stated or implied that there is no crew on board the autonomous vessel, such as: "one could think that the autonomous ship would be the solution to this kind of unlucky events, because it is unmanned", *Ahvenjärvi (2016)*; "First, the lack of human presence on-board may render the proposed autonomous ships unseaworthy[…]", *Carey (2017)*. In only two articles is the separation between the terms not or insufficiently discussed. Five articles state that autonomous does not necessarily mean unmanned. In four of these five, there is clear separation between autonomous and unmanned in general. The last of these five articles makes statements elsewhere in the text implying that autonomous is unmanned. There is a clear tendency for articles published later to clearly separate autonomous from unmanned, while the earlier articles generally do not.

Two papers consider remote controlled operation to be a level of autonomy that is not fully autonomous, while two papers do not distinguish between remote controlled operation and autonomous operation. Three articles do not consider remote controlled ships to be autonomous.

4.3.1. Benefits and challenges of autonomous ships in scientific papers

Of the expected benefits of autonomous ships, improved safety for the ship and people is mentioned in six out of the twelve papers. Four papers state that accidents due to human error will be reduced on autonomous ships, while three papers challenge this notion. One paper refers to statements that support both views. Three papers expect autonomous ships to result in improved fuel efficiency, while increased operational efficiency is only mentioned once. Lower crew costs are mentioned as a benefit in five papers and another expects lower operational costs in general, which could encompass crew cost, although this is not specified. The possibility of eliminating hotel systems due to the absence of crew on board is mentioned three times, and the possibility of carrying more cargo due to not having an accommodation is stated in two papers. The benefit of increased reliability on autonomous ships is mentioned only once. Three papers mention the autonomous ship having a positive impact on the expected shortage of seafarers in the future.

The most frequently mentioned challenge in the development of autonomous ships is that maritime legislation not allowing for autonomous operation. This issue is mentioned in eight of the twelve papers, while data security is mentioned as a challenge in four. The business case of the autonomous ship being uncertain is mentioned as an issue in two papers. The man-machine interface between the autonomous ship and remote or onboard operators is mentioned as problematic in two papers also. Three papers state that the building cost of an autonomous ship will be higher than that of a conventional ship, while one expects it will be lower. The public's perception of autonomous ships as being unsafe and the public's perception of autonomous ships putting people out of jobs is both mentioned in three papers.

4.4. News sources

Popular news articles contain views, opinions and statements from many different sources. The short format of a news article does not allow for exhaustive elaboration on or definitions of all the topics discussed. Journalists may quote out of context or paraphrase sources, giving an inaccurate representation of the originally intended message. Perceptions and statements on autonomous ships presented in news articles should therefore be treated with some caution. The analysis shown in Table II, however, presents some interesting trends when all twenty-three news articles are considered together. Of the twenty-three articles, ten quotes, paraphrases or contain interviews with representatives from Rolls-Royce. Six articles contain statements from shipping companies and nine others from the remaining sources, Kongsberg, Yara, MacGregor, Wärtsilä, Norled, labour unions and authorities.

In three articles, the term smart is used either as an overarching term that encompasses the autonomous ship or synonymously with autonomous ship. The term intelligent ship is used in two.

Ten articles use the words automation or automated in the discussion of autonomous ships. In none of these ten articles is there a clear distinction between the two terms. In some articles, the words seem to be used synonymously, such as here: "despite the fact that ULCVs [Ultra Large Container Vessels] would not opt for full automation they are likely to adopt many parts of R&A [Remote and Autonomous] technology", *World Maritime News (2018b).* In other places, it appears that autonomous and/or unmanned operation is the end result of increased automation, such as "the ongoing push toward automation of ships is not likely to result in crewless containerships anytime soon […]", *World Maritime News (2018a)*. From the analysis, it does not appear that using autonomy and automation synonymously is becoming less prevalent with time. There is unclear separation between the terms in six out of the nine articles published in 2018. Of the articles published before 2018, there is only unclear separation in four out of fourteen.

There is generally very little distinction between the terms autonomous and unmanned in the news sources. In only two articles is it clear that autonomy does not mean unmanned. In one of these two articles, a quote from another source ties unmanned to autonomous elsewhere in the text, meaning the article displays both "clear" and "unclear separation". In five cases, however, it is indicated that an autonomous ship is not necessarily unmanned all the time, and that autonomous technologies could be applied on manned vessels. In all these five articles, statements implying that autonomous is unmanned are found elsewhere in the text.

In five articles, the term "fully autonomous" is used in a context meaning both unmanned and not remote controlled. The term is used often when referring to the Yara Birkeland project: "Yara Birkeland will initially operate as a manned vessel, moving to remote operation in 2019 and expected to be capable of performing fully autonomous operations from 2020," *World Maritime News (2017b).* A vessel under fully autonomous operation is an unmanned vessel when presented in this way.

If remote control is autonomous operation or not is the matter of some contention. Five articles make this distinction, while three treat remote control as being some form of autonomy, such as here: "Japanese shipping company Nippon Yusen Kabushiki Kaisha (NYK) intends to test an autonomous containership in the Pacific Ocean in 2019. […] The boxship, the size of which has not been specified yet, would be remotely controlled", *World Maritime News (2017a).*

4.4.1. Benefits and challenges of autonomous ships in news sources

When considering the perceived benefits of autonomous ships, safety for ship and crew is mentioned most often, appearing in eleven articles. However, one source also questions the truth in this claim. In eight cases, it is specified that this improvement in safety is the result of reduced human error as the human operator is removed. This claim is contested in two articles. A reduction in fuel consumption is mentioned seven times, while optimising operational efficiency is highlighted in six articles but also challenged in one. Regarding other benefits, reduced crew costs have four mentions, while higher cargo capacity and a reduction in the number of hotel systems because of not having an accommodation are mentioned two and five times respectively.

Regarding challenges in the development of autonomous ships, the fact that the business case is not yet clearly proven is mentioned most frequently. This issue is pointed out in eight articles, while the issue of maritime legislation not accommodating autonomous ships is mentioned in five. Other highlighted challenges are data security at two mentions, and operator skill degradation and public perception at one mention each.

5. Discussion

From the analysis, a general agreement on some aspects of the autonomous ship is seen. The autonomous ship is expected to require a large degree of mechanical redundancy, it will require more advanced automation and more sensors, and it must be possible to monitor it constantly from shore. Dynamic positioning is mentioned as a probable necessity in both the MUNIN and AAWA projects. There is also agreement on the need to be able to control the vessel remotely from an on-shore control centre, although whether remote controlled operation constitutes autonomy is a point of contention.

Whether the autonomous ship is unmanned or not is another aspect, and a vital one, where there is little agreement. This issue is crucial since most of the expected benefits of the autonomous ship originate from there being no people on board. Some say that autonomous means unmanned, while others say that it definitely does not. Many sources, however, are either vague about the distinction or say that autonomous may be manned in one place in the text but then use autonomous and unmanned synonymously in another. This ambiguity is found in all three categories of research projects, scientific literature and news articles. In the scientific literature, there is a trend of the latest papers being clearer in their separation of autonomous and unmanned. It could be that there is a growing awareness of the need to clearly define autonomy in the context of these papers due to the term's perceived ambiguity. This trend is not seen in the news articles. In the news, there is a tendency towards increasingly unclear separation between automation and autonomous. It could be that the definition of autonomy has increasingly come to mean something that is closer to automation and that the two terms are now used synonymously. It could also mean that there is a growing awareness that what has previously been discussed as or attributed to autonomy is in fact automation.

The trends seen in Tables I and II relating to the separation of the terms automation and autonomous, and in particular between autonomous and unmanned, are not reflected in the expected benefits. There is a big difference in how many and which benefits and challenges are mentioned in the papers and articles, likely depending on the subject. Some benefits seem to group together: the lack of qualified seafarers only appears in the first half of Table I, but it is hard to see any clear trends in general. Regarding the challenges, one development stands out. An unproven business case appears only in the second half of both tables but is mentioned frequently, in eight out of thirteen articles, in Table II.

Much of what autonomy is expected to bring is related to unmanned operation. Removing the accommodation and eliminating the hotel systems is only possible if the vessel is completely unmanned. Without doing this, the benefits of a simpler, more reliable ship that is cheaper to build, with more room for cargo and more fuel efficient due to lower weight and less wind resistance cannot be claimed.

Some benefits can only be partially claimed if the crew is merely reduced. What can be saved in terms of crew costs, and with this the increased incentive for slow steaming due to reduced crew costs as mentioned in MUNIN, is uncertain if it is not specified to what extent the crew size is reduced. If there is still a crew on board, they will also still be subjected to the hazardous working conditions at sea and there is still an expected shortage of seafarers in the future to account for.

With humans in the operating loop the benefit of increased safety for the ship and people due to reduced human error is also uncertain. Without specifying exactly which processes will be made autonomous it cannot be determined if and how autonomy will result in reduced human error. Increased safety is the most frequently mentioned benefit of the autonomous ship, but it is also the most contested.

Other of the expected benefits of the unmanned and/or autonomous are effects derived from having to make vessel simpler, with more redundancy and a greater number of sensor points that could arguably be achieved equally well on a conventional manned vessel. One example is the simpler and more reliable fuel system due to running on diesel instead of heavy fuel. Optimised route planning and weather routing along with better condition monitoring and management of machinery are the result of more sensors and better data processing, which does not require the ship to be unmanned or even autonomous in any way. The same is the case for more effective pooling, new leasing opportunities and better online cargo services as a result of greater data flow as mentioned in AAWA.

This does not in fact leave many of the perceived benefits of the autonomous ship. Increased operational efficiency and better operational reliability remain, although it is not always clear from the material exactly how autonomy will contribute to this.

5. Conclusion

There is some common understanding of the overall concept of the autonomous ship but there is no consensus as to whether an autonomous ship is unmanned or not. There does seem to be a growing awareness of the necessity to separate the terms within the scientific material, although this understanding has not permeated through to the news media. The changing perception of the autonomous ship not necessarily being unmanned, however, has not changed the expectations of what autonomy has to offer the maritime world. Whether an autonomous ship is unmanned or not has a huge impact on the benefits that can be expected. Most benefits of autonomous ships found in the analysed material are in fact related to the lack of crew on board.

What an autonomous ship is if it is not unmanned is not clear from the analysed material. IMO, classification societies and researchers have already done much to define the autonomous ship and autonomy levels. This paper emphasises the importance of this work, but it is also clear that these definitions have not been fully absorbed by the broader public yet. Efforts should be made to precisely define which kind of autonomy is being discussed in each case to avoid supporting or creating unfounded expectations. Perhaps the term autonomy should be used with greater caution in general, especially when describing systems that could more accurately be defined as automated.

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Table I: Analysis of scientific material

		Automation Vs. autonomy			Unmanned Vs. Autonomous									Benefits										Challenges						
Reference	Date	No or unclear separation	Clear separation	Not discussed or insufficient	No or unclear separation	Clear separation	Fully autonomous Is unmanned	Autonomy Is not necessarily unmanned	Remote is an autonomy level	Remote is autonomous	Autonomy is a scale	Not discussed or insufficient	Smart	Safety (ship and or crew)	Human error	Efficiency (operation)	Efficiency (fuel)	Crew cost	Hotel systems	More cargo	Reliability	Operational costs	Lack of qualified seafarers	Data security	Legislation	Unproven business case	Human machine interface	Higher building costs	Public perception safety	Public perception losing jobs
Hooydonk (2014)	xx-xx-2014			x								x[1]	x		x/z									x	x				x	x
Jesus et al. (2016) (COMPIT)	09-05-2016			x		x		x	x		x			x	x			x					x		x			x		x
Ahvenjärvi (2016)	xx-09-2016			x	x			x		x					z		x					x					x			
Hogg and Ghosh (2016)	06-09-2016	x			x								x	x	z			x	x				x	x	x		x	x		
Carey (2017)	xx-xx-2017			x	x						x								x	x					x			z		
Rahav (2017) (COMPIT)	15-05-2017			x	x					z	x			x	x			x					x							
Singh et al. (2017) (COMPIT)	15-05-2017			x	x																									
Varas et al. (2017) (COMPIT)	15-05-2017			x	x																									
Wróbel et al. (2017)	xx-09-2017			x		x	x	x		x				x	z									x	x				x	
Kobylinski (2018)	16-03-2018			x		x		x		z			x											x	x	x				x
Merenluoto (2018) (COMPIT)	14-05-2018			x		x		x	x	z	x			x	x		x	x	x		x				x				x	
Benson et al. (2018)	xx-06-2018			x								x		x	x	x	x	x		x					x	x		x		

z means that the opposite of the statement in the column is expressed

[1] Article is on unmanned merchant shipping. Talks of autonomous ships as being one kind of unmanned ships but makes no statements of autonomous ships being always unmanned. Also, does not say that autonomous ships can be manned. Does not use unmanned and autonomous interchangeably.

Table II: Analysis of news articles

Reference	Date	Source (Quote/interview/paraphrasing)							Automation Vs. autonomy			Unmanned Vs. Autonomous						Terms		Benefits							Challenges				
		Class/authorities	Union	Others	Shipping company/operator/owner	Rolls-Royce	Yara	Kongsberg	No or unclear separation	Clear separation	Not discussed or insufficient	No or unclear separation	Clear separation	Fully autonomous is unmanned	Autonomy Is not necessarily unmanned	Remote is autonomous	Not discussed or insufficient	Smart	Intelligent	Safety (ship and or crew)	Human error	Efficiency (operation)	Efficiency (fuel)	Crew cost	Hotel systems	More cargo	Data security	Legislation	Unproven business case	Skill degradation	Public perception
The Economist (2014)	08-03-2014					x			x			x				x				x	x		x	x	x	x	x				
The Motorship (2014)	21-07-2014	x							x			x		x						x											x
World Maritime News (2016)	14-10-2016					x					x						x	x													
Levander (2017)	28-01-2017					x					x	x			x	z			x	x	x	x	x		x	x		x			
World Maritime News (2017c)	23-03-2017			x[1]		x					x						x			x		x									
World Maritime News (2017f)	28-03-2017					x					x						x	x				x									
World Maritime News (2017g)	09-05-2017						x	x			x	x		x		z															
World Maritime News (2017a)	11-07-2017				x						x	x																			
World Maritime News (2017d)	25-08-2017				x						x					x	x			x	x										
World Maritime News (2017h)	28-09-2017						x				x	x		x		z															
World Maritime News (2017b)	06-11-2017		x						x			x						x		x/z	x/z		x				x	x	x	x	
World Maritime News (2017e)	09-11-2017		x						x								x					x/z							x		
Pico (2017a)	16-11-2017										x					x	x														
Pico (2017b)	20-11-2017				x	x					x	x	x[2]		x							x	x					x	x		
World Maritime News (2018b)	08-01-2018				x						x	x																	x		
World Maritime News (2018a)	16-02-2018				x				x					x		z				x	x/z								x		
Willumsen (2018a)	06-03-2018										x	x[3]			x					x	x		x	x	x				x		
Willumsen (2018b)	13-03-2018										x	x																	x		
World Maritime News (2018c)	14-04-2018				x	x			x			x		x	x					x	x		x	x	x						
CNBC (2018)	23-04-2018					x			x			x		x	x					x	x		x	x	x						
Pico (2018)	02-11-2018					x			x			x				z			x									x	x		
Wärtsilä Corporation (2018)	28-11-2018	x		x[4]					x				x							x		x									
Bartlett (2018)	03-12-2018					x			x								x						x					x			

z means that the opposite of the statement in the column is expressed

[1] MacGregor
[2] Quotes both person from Svitzer that makes clear distinction between unmanned and autonomous and person from RR that does not
[3] Does talk about manned autonomous vessel, but maintain referring to benefits from unmanned ship from unmanned operation
[4] Wärtsilä and Norled

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Paper II

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On-board Human Operators: Liabilities or Assets?

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Abstract

This paper analyses data from cargo ships in order to investigate how unmanned operation will impact the ability to detect and prevent near miss incidents from developing into marine accidents. Many claim that eliminating the presence of an on-board crew will eliminate accidents caused by human errors. Others caution that human error may not disappear with the elimination of the crew and that new incidents may occur because of it. The analysis finds that on-board human presence is attributable to some errors but that it at the same time is vital for detecting and stopping the development of incidents.

1. Introduction

Unmanned and autonomous ships are expected by many to revolutionize the maritime industry in the coming decades. With improved sensor and computing capabilities together with the elimination of the on-board crew, the ships of the future are expected to be safer and more efficient with regard to both operation and energy consumption, e.g. *Rødseth et al. (2012)*. There is, however, still considerable ambiguity in the use of the term autonomy in the maritime context. It is often claimed that autonomy does not imply unmanned operation but many of the expected benefits of autonomous operation come from the absence of crew and of the accommodation of the crew on board, *Eriksen (2019)*. One of the most frequently claimed benefits of the autonomous and/or unmanned Ships (UMS) is the elimination or at least reduction of human error. An estimated 75% - 96% of all marine accidents can be attributed to human error, *Allianz (2017)*, and it seems an obvious solution to simply remove the crew, and therefore the human element, from the Conventionally Manned Ships (CMS). Others, however, warn that it is not so easy. *Ahvenjärvi (2016)* explains that there is human interaction in all aspects of marine operation, not just the day-to-day on-board operation, and that all aspects are subject to human error. He explains that removing the crew may simply shift the human error from the ship's crew to the control room personnel, designers, programmers and maintenance personnel responsible for operating, designing and maintaining the UMS.

Even if the majority of accidents can be partly or fully attributed to human error, the onboard crew are often vital in the mitigation of consequences when accidents happen. *Wróbel et al. (2017)* examine 100 maritime accident reports and assess whether the accident would have happened on a UMS, and once it had - would its consequences have been different if there had been no one on board to counteract them. They conclude that the number of navigation-related marine accidents such as grounding or collisions may be reduced on UMS but that the consequences of the accidents will be greater due to limited possibilities for consequence mitigation. *Wróbel et al. (2017)* go on to explain that their study is limited in that they were only able to investigate incidents where accidents did happen and not when crews were successfully able to prevent an accident from happening.

It is fortunately the norm that ship operate without incidents or accidents for the overwhelming majority of the time. From time to time incidents happen that require the crew to react to prevent danger to the ship, crew or environment. Most of the time these incidents are dealt with without consequences to the ship, crew or environment and without the need to involve external parties or the authorities. The body of evidence on maritime accidents is very one-sided in that it mainly contains reports on instances when things go wrong, not when they go right. This paper will attempt to bridge that gap by examining incidents that were close to resulting in an accident but where an accident was prevented. By analysing reports on near miss incidents from ships this paper will investigate the role played by the on-board crew in the occurrence and detection of incidents. The paper will also evaluate how unmanned operation affects the ability to stop an onboard incident from developing into a maritime accident.

2. Theory

In this section the theoretical background for the analysis in this paper is presented. In Section 2.1, a brief explanation of the concept of a near miss is given and the rationale behind the reporting and processing is described. In Section 2.2, the conceptual accidents model used throughout this paper is introduced.

2.1. Near Miss

A near miss is described by *IMO (2008a)* as "A sequence of events and/or conditions that could have resulted in loss. This loss was prevented only by a fortuitous break in the chain of events and/or conditions". The loss can be human injury, environmental damage, or negative business impact. Reporting of near miss occurrences is a mandatory part of The International Safety Management (ISM) Code, *IMO (2008b)*, and serves to improve the safety of ships by learning from past experiences. Ships must report near misses to the company office, which must analyse and make or amend procedures or recommendations based on these. The object is to identify unsafe conditions and prevent the hazardous situation, event or unsafe act from occurring again, and perhaps this time resulting in a loss. The interest in reporting and investigating near miss incidents also stems from the idea that even though the near miss itself does not have consequences, there is proportionality between near misses, minor incidents and major accidents. This concept is called the "iceberg model" or "accident pyramid" and is developed by *Heinrich et al. (1980)*. An example of Heinrich's Pyramid can be seen in Fig.1.

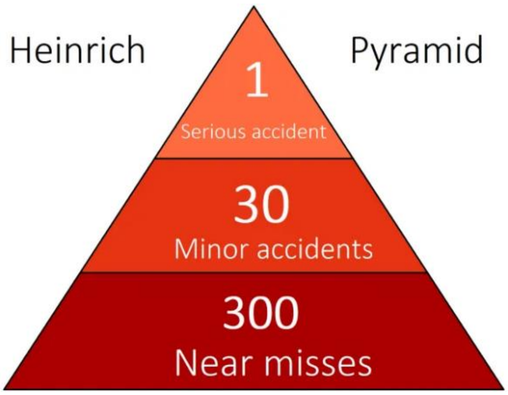

Fig.1: Heinrich's accident pyramid, *Colins (2018)*

The understanding of accident prevention has moved on since the pioneering work initially begun by *Heinrich et al. (1980)* in the 1930s. It is now widely accepted that the linear causal understanding of accidents that Heinrich proposes, and that the accident pyramid implies, is over-simplistic and does not accurately describe the complex failures of intricate systems, *Salminen et al. (1992)*. The ratio of major to minor accidents and near misses varies greatly across industries and the causes of minor incidents and major accidents are often not the same, *Hale (2002)*. Some, but not all major accidents can be predicted by minor accidents, and not all minor accidents have the potential to develop into major accidents.

Major accidents are often a consequence of a combination of unlikely circumstances and frequently come as a fundamental surprise to the operators, according to the "Normal Accident Theory", *Perrow (1999)*. It follows that the magnitude of accidents that were prevented from happening for one reason or another may not ever be realized. It may indeed never even be noticed that a major accident was close to occurring at all.

Evaluating safety performance based on the rate of near misses and/or minor incidents alone is a poor but often used practise, *Hale (2002)*. One issue is the tenuous relationship between minor and major incidents mentioned above. Another equally important issue is the discrepancy between actual and reported incidents. There are many reasons why near misses are not reported. Sharing the experience of an accident that nearly happened with the rest of the company could ideally prevent it from happening again, this time perhaps with serious consequences. There is, however, no obvious short-term incentive for the individual employee or supervisor to report the incident. The individual may also fear being blamed, disciplined, embarrassed or found legally liable, *IMO (2008a)*. If individuals feel that the company is unsupportive, complacent or insincere about addressing safety issues, they may be less inclined to use their often already busy work time on reporting.

The quality of reported near misses can also vary greatly. To incentivise reporting many companies require a minimum number of reports per month per ship. Some incidents may therefore be reported to satisfy a quota rather than because there is anything to be learned from them. The definition of a near miss can also be ambiguous. Some companies distinguish between unsafe conditions, unsafe acts, near misses, minor incidents, near accidents, etc. but others do not. Determining what qualifies as which, if any category, can be challenging. The reporting system for near misses is also sometimes used to report issues that do not qualify as near misses or are not directly related to safety. If a request for spare parts or service on equipment is not being met, for example, the ship's crew may deliberately use the near miss reporting system to circumvent the normal communication channels in the company. Safety-related issues are often referred directly to a senior safety officer rather than to the ship's superintendent.

Near misses are not a perfect representation of how exposed an organization is to major accidents but all of these reservations aside, there is good evidence for the importance of near miss reporting as a tool to improve safety, *Jones et al. (1999)*.

2.2. Bowtie method

One commonly used risk evaluation method to evaluate and understand causal relationships in high-risk scenarios is the bowtie method, an example of which can be seen in Fig.2. The method is named after the shape, which resembles a bowtie. Causes, also called threats, are on the left and Consequences, also called outcomes, are on the right. In the centre the bowtie converges in a Critical Event which is also called the top event, central event or centre event. The Critical Event can be defined as a release of hazardous substance or energy, *Markowski et al. (2009)*. Between the Causes and the Critical Event and between the Critical Event and the Consequences there are a number of Barriers. A Barrier is in place to prevent, control or mitigate the release of energy or hazardous substance. Barriers can be physical barriers or other physical equipment, or they can be non-physical, such as procedures or policies.

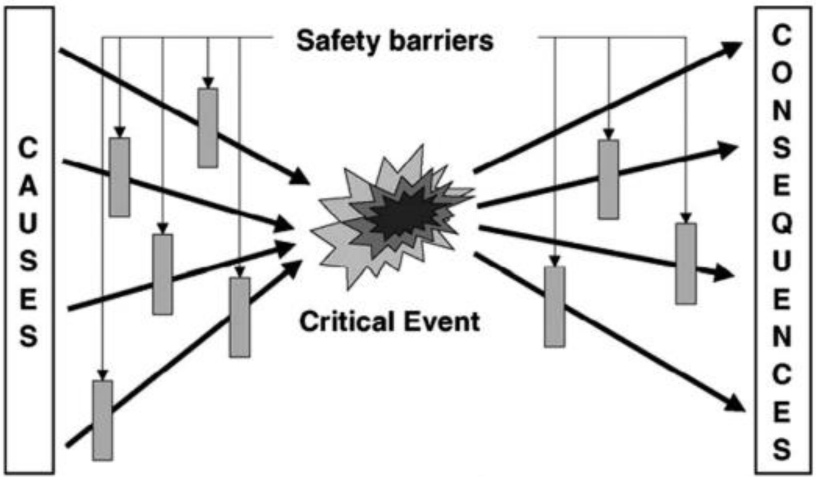

Fig. 2: Generic example of a bowtie, *de Dianous et al. (2006)*

The overall idea behind the bowtie method is that there can be several Causes of a Critical Event and that a Critical Event can have several Consequences. A Critical Event could be a fire. There can be many Causes of a fire breaking out and there can be many Consequences of the fire depending on the Barriers that are in place to control, contain or mitigate the fire. By focusing on the Critical Event, it becomes evident whether there are sufficient Barriers in place.

Although it is possible to define Causes, Critical Event and Consequences in the bowtie method, it can be difficult to distinguish clearly between the categories, *de Ruijter et al. (2016)*. Depending on the perspective chosen for the analysis, an electrical blackout on a ship, for example, could be described as all three categories. The Cause could be low lube oil level, the Critical Event could be low lube oil pressure and the blackout would then be the Consequence. If the blackout were the Critical Event, the Consequence could be grounding or collision. The grounding or collision could also be the Critical Event that had an oil leak or structural damage as a Consequence and the blackout as a Cause.

The bowtie model can be used both quantitatively and qualitatively. In this paper, it is used as a conceptual understanding of the development of accidents.

3. Data and data collection

The basis of this paper is the analysis of near misses. Safety-related information such as near misses often contains sensitive business information and is not normally publicly available, but one company was generous enough to supply near miss reports for the purpose of analysis. The name and operating segment of the company will remain anonymous, but the company operates one segments of cargo ships trading costal and worldwide. A total of 7205 near misses was initially examined. The near misses originated from 28 different vessels over a total of 126.9 years of operation between the start of 2012 to the middle of 2019.

The near miss reports consist of a brief Subject description averaging seven words and a slightly longer Description averaging 29 words. There are also accounts of the Immediate cause, Underlying cause and Corrective actions averaging 11, 20 and 16 words respectively. The length and detail of all the categories vary greatly, the shortest consisting of just one word while the longest contains more than 500 words. The date and time of the reports are available but details of position, operating mode, time of incident, weather conditions and other specifics are only occasionally included in the text, presumably if they are deemed to be of importance to the report.

4. Methodology

This section describes the method used in the analysis of near miss reports in this paper. Section 4.1. describes the operational scenario through which the analysis is done. In Section 4.2. the initial selection of near misses for analysis is described and in Section 4.3. the further categorization of the near misses is explained.

4.1. Scenario

The intention of this paper is to evaluate the UMS as being as close to the CMS as possible. Some assumptions about the on-board equipment and operation of the UMS must however be made for the purpose of the analysis. The operational scenario is based on that described in the project Maritime Unmanned Navigation through Intelligence in Networks, http://www.unmanned-ship.org/munin/partner/. In the scenario the UMS is assumed to be unmanned during sea passage in open sea, but is manned, remote-controlled or continuously monitored from shore during manoeuvring in and out of port, in narrow or heavily congested waters and while alongside berth. The shore control centre has access to all the inputs from the engine monitoring and alarm system of the UMS as well as all the bridge equipment. The control centre can start, stop and operate all the electronic or electronically actuated equipment as the on-board crew would normally do. It must also be assumed that the control centre can manipulate at least some of the valves, fire flaps, control levers, etc. that the crew normally operate manually. Some kind of video surveillance system is also assumed to be installed on board. When operating unmanned, the ship is assumed to be able to perceive and react to other vessels or objects and be able to react to the situation without outside control in the same way as a navigating officer would or to convey the information to a shore control centre that can then take over the control of the vessel. The placement, quantity, quality and maintenance regime of all machinery equipment on the UMS is assumed to be identical to that of the CMS except for remote control and monitoring capabilities. The added complexity and possible additional sources of failure resulting from the remote monitoring and operation capabilities are not considered.

4.2. Initial selection

As described in Section 2.2, it can be difficult to distinguish between Causes, Critical Events and Consequences in the bowtie model. This is especially true for near misses where the event was interrupted before it could develop into its full consequence. It is, however, not essential to distinguish between Causes, Critical Events and Consequences in this analysis. What is important is to differentiate between what will be described here as Active Events, which are those that can fall into the three categories mentioned above, and Passive Events which relate to the barriers. Active Events are non-routine events that will develop into a dangerous situation if not detected and stopped. Missing or defective barriers are Passive Events that, although they can be critical, will never in themselves develop into an accident without some other initiating event. Only Active Events are included in the analysis.

What the bowtie method described in Section 2.2. also shows is that there can be many different outcomes from one Critical Event. It is very hard to accurately estimate what the consequences would have been if they had been allowed to develop. In some cases, the event would have been close to resulting in a major accident, in other cases they may have been caught by another barrier before any consequences occurred. Only incidents that, if not detected and stopped, could plausibly result in very serious casualties or serious casualties as defined in *IMO (2008b)* "Casualty Investigation Code" are included. No ranking of criticality was done due to uncertainty about the possible consequences. Marine accidents as defined by *IMO (2008b)* are those that involve "Fire, explosion, collision, grounding, contact, heavy weather damage, ice damage, hull cracking or suspected hull defects etc." Incidents that would "only" result in harm to single individuals, and not the ship and/or crew as a whole are not included.

4.3. Categorization

The categorization of the near misses was done in four steps. Near misses were first categorized into types of comparable incidents. There are large variations between the reported near misses and exact evaluations of the criticality and likely consequences of each incident were not possible, as described in Section 4.2. The incidents within each type were assessed to be sufficiently similar to make more generalized assessments of each type as a whole.

In the first categorization step, the outcomes from the initial selection were categorized into three near miss types; Fire, Flooding and Contact. The three types follow those of the marine accidents as described in Section 4.2. but are simplified into fewer categories since it is not possible to precisely predict what the outcome would have been had the near miss been allowed to develop into a marine accident.

The Fire category, which also includes the marine accident category Explosion, comprises incidents which could have resulted in a fire due to unattended or improper use of equipment, dangerous working practices, heavy running of equipment, short circuit or malfunction of electrical components and fuel oil leaks. Lubrication oil leaks are also included if they are specified as being near to a source of ignition such as a hot exhaust pipe. Improper storage of materials including garbage and oily rags is also included in the Fire category.

The Flooding category includes open watertight openings, corrosion or failure of material containing water and incorrect working practices leading to internal leaks.

The Contact category is an amalgamation of the marine accident categories Collision, Grounding and Contact. Incidents include broken mooring lines, miscommunication and human error during manoeuvring, faulty navigation, propulsion and steering equipment failure in confined waters, other vessels' dangerous movements and own vessel dragging anchor.

In the second step it was noted whether the near misses were related to equipment that can be described as "crew comfort equipment" such as tumble dryers, bread toasters, cooking stoves, ovens and other galley equipment. It is highly unlikely that equipment such as this will be installed on a UMS and that it will be in use during unmanned operation if it is installed. The position or operating mode of the vessel at the time of the near miss is also noted when available in the near miss reports. Positions or operating modes are divided into the categories Sea, Anchor, Port and Manoeuvring which also include operation in restricted waters and channels. It is also noted whether the near miss is discovered by on-board Human Presence or by an existing Alarm or Measuring Point.

The third step is an evaluation of the cause of the near miss and is grouped into Human Error, Equipment Failure or External Influence, the latter meaning another ship, object or an extreme meteorological event. Only the immediate cause of the near miss is evaluated as the available data does not support a deeper analysis into the underlying causes. If an immediate cause cannot be established from the data, it is marked as unknown.

In the fourth and final step an evaluation is done of the effect of unmanned operation on the possibilities for stopping the development of the incident. This evaluation is based on the assumptions of the capabilities of the UMS described in the operational scenario in Section 4.1. as well as knowledge of the capabilities and design of machinery systems of the existing manned ship. This evaluation relies very much on the engineering knowledge of the author. The author has ship-specific knowledge of one of the ships from which the data originated as well as general knowledge about the construction and operation of marine systems in general from multiple other vessels of similar design. The evaluation is done based on the assumption that the design of the remaining ships from which the near miss data originated is not fundamentally different from that which is common in this type of vessel. This final step includes an evaluation of whether the possibilities of stopping an incident developing on a UMS would be Better, the Same or Worse compared to a CMS. A fourth category, Contain, was introduced meaning that the incident could probably be contained and not develop and cause further harm but could not be repaired until crew entered the UMS again.

5. Presentation and discussion of results

The initial selection described in Section 4.2 resulted in 481 near misses chosen for analysis. This means that only 6.7% of the total amount of 7,205 near misses met the sorting criteria. Some reported incidents were not safety-related and did not fall under the IMO definition of a near miss. Many incidents were related to incorrect work procedures and could or did only result in minor personal injuries such as cuts or slips. The majority of near misses were excluded because they only related to missing barriers such as missing personal protection equipment or broken or missing safety or monitoring equipment.

5.1. Near miss by type

Categorizing the near misses results in the distribution seen in Figure 3. The largest segment is Fire, which represented 40% of the near misses. Flooding, which represented 36%, is the second largest segment and the remaining 24% related to Contact. Of the 481 near misses analysed, 65 were related to equipment that can be described as "crew comfort equipment". All of these 65 near misses were in the Fire category and constitute 14% of the total number of near misses and 33% of the number of near misses in the Fire category.

For the comparison of the distribution of near misses to actual accidents, Fig.4 shows the distribution of global accidents. The accidents included in Fig.4 are those categorised as "very serious" and "serious" and that fall into the same three categories as the analysed near misses. The data is taken from European Maritime Safety Agency, *EMSA (2014)* and originates from the years 2011 to 2013. It is clear that there is a large discrepancy in the distribution of categories between the analysed near misses and actual reported accidents. One likely cause of this discrepancy is different ratios of minor incidents to major accidents for different segments as described in Section 2.1. It may be that there are generally more near misses per actual accident for the near miss types Fire and Flooding than for Contact. Ships often operate close to other ships or structures or with very little under-keel clearance. This is regarded as part of the normal operation but when things do go wrong there is very little margin of error. Fire and Flooding incidents are not part of the normal operation, so when a potential fire or flooding hazard occurs it is immediately rectified and reported. For Fire especially it is also likely that the bar for when an incident is considered potentially dangerous is very low. Fire is often described as the seafarer's worst nightmare and so even minor deviations are likely to be reported. For Flooding, unless it is very severe, there will typically be ample time to rectify the damage and in most cases, it will be possible to stop the near miss from developing into an accident.

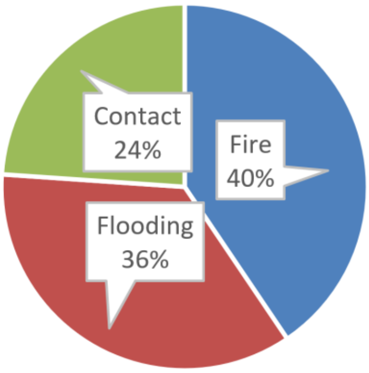

Fig. 3: Near misses by type – this analysis

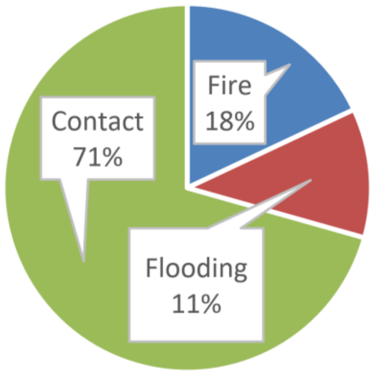

Fig. 4: Accidents by type - global values 2011-2013, *EMSA (2014)*

5.2. Position of ship at occurrence of near miss

Table I shows the reported position of the ship at the time at which the near miss occurred. For the majority of near misses relating to Fire and Flooding, no position was reported. It is likely that the particular position or operating mode of the ship was not judged to be of importance to the occurrence and possibility of rectifying the incident and was subsequently not reported.

For near misses relating to Contact, the position can always be inferred from the data, which makes sense since the traffic situation and/or geographical position is important to the understanding of the near miss. In only 8% of the situations where the ship was close to a collision with another ship or structure or close to a grounding, the vessel was in open sea. For the rest of the incidents, the vessel was either at anchor, manoeuvring into or out of port, transiting canals or other narrow passages or moored alongside a dock in port.

Table I: Position of ship at occurrence of near miss

	Sea	Anchor	Manoeuvring	Port	Unknown
Fire	14%	2%	2%	3%	79%
Flooding	30%	2%	3%	6%	59%
Contact	8%	14%	61%	17%	0%
Total	18%	5%	16%	8%	53%

5.3. Discovering near misses

Table II shows the means by which the near misses were discovered. There is some variation in the values across the categories, but the vast majority were discovered by human presence for Fire, Flooding and Contact. More near misses related to Flooding were discovered by an alarm or measuring point than for the other two categories. This is probably related to the fact that a near miss reported on Flooding almost always relates to an actual leakage as opposed to those reported on Fire for example, which often relate to immediate fire hazards but without the outbreak of an actual fire. If left undiscovered and unattended, a leak will eventually result in a bilge alarm.

Table II: Discovery of near misses

	Human presence	Alarm or measuring point	Unknown
Fire	94%	6%	0%
Flooding	77%	19%	4%
Contact	91%	5%	4%
Total	87%	11%	2%

All near misses are analysed based on the available material and it is possible that an alarm gave notification of the incident but that this was not reported in the data. This is especially relevant for near misses relating to Contacts. Alarms on radars and electronic chart displays can be customized to warn of close, or projected close proximity to other objects. This is a helpful feature in open sea where a large berth can and should be given to other ships and objects. In manoeuvring operations or when travelling in restricted water, however, ships are routinely required to operate much closer to other objects than would be regarded as safe in open sea, as also explained in Section 5.1. The evaluation of whether a situation is dangerous or safe relies on the interpretation of many different inputs about the actual situation and not least about the intended future actions of own and other vessels. Proximity alarms from radars and electronic chart displays are of very little value in these situations and are generally ignored or disabled.

5.4. Cause of near misses

Table III shows the causes of the analysed near misses across the three near miss types. Human Error is responsible for between 29% and 45% of the near misses. Equipment Failure is responsible for the majority of Fire and Flooding-related near misses but for only 14% of those related to Contact. Nearly half of Contact-related near misses, but virtually none relating to Fire and Flooding, are caused by External Influence.

Table III: Causes of near misses

	Human Error	Equipment Failure	External Influence
Fire	45%	55%	0%
Flooding	29%	69%	2%
Contact	42%	14%	44%
Total	38%	50%	11%

The number of near misses caused by Human Error across all three categories is lower than the corresponding value for incidents that resulted in actual accidents. Human Action was an Accident Event or a Contributing Factor to 65.8% of analysed marine accidents in 2018, according to *EMSA (2019)*. This discrepancy is probably due to a combination of different factors. Reporting bias must certainly be considered as one of these; individuals may be more inclined to report on equipment failures or failures resulting from external influences than on their own or their colleague’s unsafe behaviour, since this could reflect badly on them personally, as described in Section 2.1. It may also be easier to define and recognize faulty equipment than unsafe behaviour.

Another factor may be that the data used in this paper did not support a deeper analysis of underlying or contributing factors of the incidents. If the data had enabled a more thorough investigation, it is possible that some near misses related to Equipment Failure would have been found to have a Human Error element due to poor maintenance or maintenance practice, wrong operation, inadequate design, etc.

The discrepancy may also be influenced by the fact that near misses in this paper are only analysed from the perspective of the vessel reporting the incident. Had an incident resulted in a collision for example, an investigation involving both vessels would have been conducted. It is likely that a large proportion of the near misses that are attributed to External Influences in this paper also have a Human Error element.

Yet another contributing factor could be that the causes of major accidents are fundamentally different from minor accidents/incidents, as explained in Section 2.1., in that the former are often a result of multiple failed preventive and mitigative barriers. One or more of these barriers are often of a human nature and therefore Human Error will be at least a contributing factor in many major accidents. Near misses are often the result of the failure of one single barrier. Other barriers, one or more of which could be of a human nature, then prevent this near miss from developing into an accident.

5.5. Stopping near misses from developing into an accident

Table IV shows the distribution of the evaluated possibility of stopping near misses developing into more serious incidents on UMS compared to CMS. Near misses that are related purely to "crew comfort equipment" have been excluded from the data in Table IV. The table clearly shows that there are large differences between the three near miss types. For Fire and Flooding it would be possible to Contain but not repair about half of the near misses. For the other half, however, the possibility of stopping the development on a UMS is evaluated as Worse.

For Contact there would be the Same possibility of stopping the incident from developing on a UMS as on a CMS for almost all the analysed near misses. This is closely related to the operational scenario, described in Section 4.1. The UMS is assumed to be either manned or remotely controlled during manoeuvring and in port. As seen in Section 4.2, the vast majority of near misses relating to Contact occur during these phases of the vessel's operation.

Table IV: Possibility of stopping development of near misses on UMS

	Same	Contain	Worse	Unknown
Fire	2%	49%	49%	0%
Flooding	0%	56%	43%	1%
Contact	97%	3%	1%	0%
Total	27%	39%	33%	1%

6. Discussion

Near misses are not a perfect proxy for the distribution and frequency of major accidents as described in Section 2.1. Most of the near misses were discarded from the analysis under the selection criteria described in section 4.2. Even among the 481 near misses that remained for analysis there may be large differences in criticality and potential severity. Some incidents may have been minutes away from developing into a serious marine accident had they not been detected and stopped. Other incidents might have been stopped by several other layers of barriers and would therefore not have had any consequences, even if they had escaped initial detection and mitigation. The estimation of criticality and severity is merely speculative, because near misses are accidents that did not happen. Near misses are, despite all these reservations, a valuable source of information about accidents that almost happened but were prevented for one reason or another. Information of this type is generally very hard to come by and has so far been missing from the discussion about unmanned operation of ships. The volume of near misses in this analysis is believed to be of a sufficient quantity to make more generalized conclusions about the nature of the detection and mitigation of the initial stages of maritime accidents. It would, however, have strengthened the analysis had near misses from other shipping companies operating other types of vessel been available.

Human Error is underrepresented in the near misses in this analysis compared to the actual accidents for all three accident types as described in section 5.4. The term human error covers a wide variety of faults, one of which is "omission", which is the failure to act. The discrepancies between near misses and actual accidents point to the role of the crew in managing to act to stop the development of incidents. Had the crew failed to act, the near miss could have resulted in an accident that would have been attributed to Human Error due to omission. The near misses attributed to Human Errors in this analysis are related to direct human actions on board as described in Section 5.4. Some of these near misses can be assumed to disappear on the UMS, but not all. Some of the near misses relate directly to the maintenance work being done on board. The majority of this work will still have to be carried out on the UMS but since it cannot be done while the ship is at sea, it will have to be compressed into the short periods when the ship is in port or close to shore. Some of the near misses attributed to Human Error will follow the maintenance work and will not disappear with unmanned operation.

Human Errors are attributable to 45% of Fire-related near misses and 29% of Flooding-related near misses in this analysis but 94% of Fire-related near misses and 77% of Flooding-related near misses are discovered by Human Presence. For almost half of the same two categories the possibility of stopping the incident developing is evaluated to be worse on a UMS than on a CMS. This has worrying implications for UMS because the majority of incidents can still be expected to occur but there are drastically limited possibilities for detecting the incidents and for stopping the incidents when they are detected. This finding supports the finding of *Wróbel et al. (2017)* in their analysis of 100 marine accidents. They find that, in general, there are more accidents that are less likely to happen on a UMS than on a CMS. For the Fire and Flooding categories in isolation however, they find the opposite to be the case. They also find that the consequences will be more severe for the majority of Fire and Flooding accidents on UMS

This analysis found that an overwhelming majority of near misses were detected by on-board human presence. This should not be taken to mean that the incidents cannot or will not be detected on UMS. Many of the near misses, especially those relating to Fire and Flooding, would eventually have been detected with the existing systems. Detecting the incidents later, however, means that they will be more developed. With more developed incidents there will be less time to stop the development of the incident into an accident. This is particularly problematic for the Fire category, where 94% of the analysed incidents were detected before an actual fire had broken out and an alarm was activated. The existing fire detection system can only warn of a fire when smoke, flame or heat has developed, at which point the incident will already have developed into, or be very close to, a marine accident. In addition to the difficulties of detecting near misses on UMS, the possibilities for stopping the development of incidents is also found to be worse for many near misses.

The possibilities for stopping incidents relating to Contact are evaluated to be the same on UMS as CMS for the vast majority of near misses. The position of the ship at the time of the near miss as described in Section 5.2. should, however, be considered because 92% of near misses related to Contact occur at times when the ship is assumed to be manned. The effect of unmanned operation on incidents relating to Contact must be considered to be very limited under the scenario described in Section 4.1. According to *EMSA (2014)*, 71% of accidents are related to Contact, but the occurrence of 92% of the Contact-related incidents in this analysis will remain unaffected by the introduction of UMS, because the ships are assumed to be manned at the time at which the incidents occurred.

In the evaluation of the possibilities for stopping the accident the Contain category was introduced, meaning that the near miss could be contained in the same way as on a CMS but not repaired while the ship was unmanned. It can be argued that this Contain category is then equal to the Same category, which is true if one looks only at the consequences of the near miss in isolation. Containing a near miss often means taking a system out of service to isolate a leak for example. There is already redundancy in many systems on CMS and stopping one system will have no direct consequences. Taking one system out of service, however, makes the ship vulnerable to failures in the remaining functioning systems. The longer the ship has to operate without the possibility of repairing the failure to the isolated system, the more exposed the ship is to experiencing failures to the remaining operational systems.

The possibility of stopping the development of incidents on UMS was not found to be greater than on CMS for any of the analysed near misses. This might seem very critical, but based on the operational scenario described in Section 4.1. it is not surprising. In the comparison, the UMS and CMS were assumed to be as identical as possible. There are really no options for stopping or mitigating accidents on a UMS that would not also be possible on a CMS. There are, however, many manual actions relating to damage control and emergency repairs that would only be possible on a CMS. Under the criteria described in Section 4.1. it would in fact be hard to imagine a scenario where the possibility for stopping the development of an incident would be better on a UMS than on a CMS.

No UMS of the scale of a modern cargo ship is in operation anywhere in the world today but a UMS would almost certainly not be designed simply as an unmanned version of today's CMS. With no actual operational data available for the UMS, however, the CMS must be used as a reference, which results in several uncertainties. The capabilities of the UMS for stopping the development of an incident are not known. Based on the results of this and other analyses, it seems likely that the UMS will have to be equipped with more redundancy in the mechanical systems and more automated or remote-controlled equipment to be able to detect and handle failures and breakdowns. These improved capabilities would favourably influence the analysis of the ability of UMS to detect and stop the development of failures. On the other hand, the added complexity resulting from these extra systems would be the cause of new yet unknown near misses. Incidents occurring because of unmanned operation represent a substantial unknown in analyses comparing UMS and CMS. Most of the reported and analysed incidents and accidents could have been prevented with hindsight and it can always be claimed that the systems on UMS will be designed so that these failures do not happen. It must be remembered, however, that the system was not designed to fail on the CMS either. The systems were designed and built to perform their task but failed to do so anyway. Construction and operation faults are almost always unexpected events that occur despite the intention of the designer and builder. Systems fail to perform as expected or are subjected to conditions that the designer did not intend. This will also be the case on UMS.

6. Conclusion

In this paper, 481 near misses are analysed in order to examine what role on-board human operators play in the occurrence and detection of the initial stages of marine accidents. The effect of unmanned operation on the ability to stop the development of incidents into accidents is also examined. Near misses are not a perfect representation of the distribution of marine accidents. Many near misses do not have the potential to develop into a marine accident and not all marine accidents can be predicted by near misses. Out of a total of 7,205 near misses, only 481 were evaluated as likely to result in a serious marine accident and were further analysed.

The near misses were divided into three types; Fire, Flooding and Contact. Compared to actual marine accidents, the near miss types Fire and Flooding were over-represented and Contact was under-represented. The explanation for this discrepancy is believed to be a combination of factors relating to the criteria for when incidents are reported. The discrepancy is also seen as evidence of the on-board human operators' role in preventing these types of incident from developing from a near miss without consequences to a serious marine accident.

It was found that 87% of near misses were discovered by humans, i.e. the on-board crew. In many cases, existing systems would probably have detected the incident eventually but only after the incident had become more severe. This is an indication of the need for significantly more monitoring and failure detection equipment on ships under unmanned operation.

For near misses related to Fire and Flooding, it was evaluated that it would be possible to contain about half of the incidents without further consequences during unmanned operation. For the other half, the possibilities for stopping the development of the accident without the presence of on-board human operators would be worse. In almost all near misses related to Contact, the possibility of stopping the development of the incident would be the same on an unmanned ship as on a manned ship. This evaluation relates very much to the finding that the vast majority of 92% of the near misses related to Contact occur when the ship is manoeuvring, at anchor or in port. The vessels are assumed to be manned during these operation phases, under the operational scenario chosen for this analysis. Unmanned operation can therefore only be expected to have little impact on Contact-related accidents. The majority of actual marine accidents are Contact-related.

Across the near miss types, 38% of incidents were found to be caused by direct on-board human error. Not all incidents related to human error can be expected to disappear with unmanned operation. At least some of the human errors must be assumed to occur following the maintenance work that, where not possible to do at sea, must be concentrated in the short periods where the ship is accessible in port or close to shore. Some near misses and accidents are direct causes of on-board human error that could be prevented if tasks could be automated, while others would be caused by the introduction of unmanned operation. Whether the introduction of unmanned operation will result in a net decrease or increase in the number of incidents and accidents is still uncertain and will depend entirely on the technical capabilities of the unmanned ships of the future. On today's conventional ships, however, with the existing technical systems, humans are vital in both the detection of incidents and the ability to stop the development of incidents into accidents.

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Paper III

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An RCM approach for assessing reliability challenges and maintenance needs of unmanned cargo ships

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ABSTRACT

Unmanned autonomous cargo ships may change the maritime industry, but there are issues regarding reliability and maintenance of machinery equipment that are yet to be solved. This article examines the applicability of the Reliability Centred Maintenance (RCM) method for assessing maintenance needs and reliability issues on unmanned cargo ships. The analysis shows that the RCM method is generally applicable to the examination of reliability and maintenance issues on unmanned ships, but there are also important limitations. The RCM method lacks a systematic process for evaluating the effects of preventive versus corrective maintenance measures. The method also lacks a procedure to ensure that the effect of the length of the unmanned voyage in the development of potential failures in machinery systems is included. Amendments to the RCM method are proposed to address these limitations, and the amended method is used to analyse a machinery system for two operational situations: one where the vessel is conventionally manned and one where it is unmanned. There are minor differences in the probability of failures between manned and unmanned operation, but the major challenge relating to risk and reliability of unmanned cargo ships is the severely restricted possibilities for performing corrective maintenance actions at sea.

1. Introduction

Autonomous and unmanned cargo ships are projected to change the maritime industry. Compared to a conventional cargo ship (CS), the unmanned cargo ship (UMS) is expected to reduce operational costs and fuel consumption and simultaneously improve safety and increase cargo capacity [1]. Others have cautioned that removing the human operators from the ship may present other yet unknown issues and that the proposed improvements may not be so easily gained. Some are raising concerns about the reliability of ship systems and the possibility of handling failures at sea without the presence of an onboard crew. Bertram [2] reasons that even if UMS could cope with all normal operation conditions, the repair of failures on these is unlikely to be handled satisfactorily. He explains that failures in existing ship machinery systems happen much too often and despite expected reliability improvements, future cargo ship operations will still be dominated by onboard maintenance. Rødseth and Mo [3] explain that the robustness of machinery systems will be a challenge for unmanned shipping.

Reliability of machinery components and the limited possibilities of dealing with failures at sea are clearly issues that must be addressed for UMS. The EU-funded project Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) concludes that a high level of redundancy in the machinery systems is required on UMS and suggests that complete redundancy of all machinery function may be necessary. An existing sea water cooling system for a CS is evaluated by Abdelmoula, et al. [4] using Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA). To achieve sufficient reliability for the system to be used on a UMS, they propose changes to the machinery arrangements through reconfiguration and added redundancy.

Reliability is considered in the design of each machinery component and the design of the vessel itself, but maintenance also affects reliability [5]. Modern cargo vessels are complex systems constructed from numerous sub-systems and individual equipment units provided by multiple different suppliers and assembled by a third party. Maintenance management systems for these vessels can be constructed by the shipping or technical management company or yet another specialised third-party company. The maintenance management systems are traditionally developed mainly based on company experience, legal or class

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requirements and recommendations from equipment manufacturers. Traditional maintenance strategies do not consider the reliability of the ship systems and sub-systems as a whole. To cope with the reliability challenges on UMS, Rødseth and Mo [3] propose that new maintenance strategies must be developed and used, and they suggest that Reliability Centred Maintenance (RCM) could be a suitable method.

The RCM method was developed in the aviation industry during the 1960s and 70 s. RCM is defined by Moubray [6] as *"a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context''*. Jones [7] further explains that a system perspective is used in the RCM analysis of system functions, failures of the functions and prevention of these failures. The background, structure and use of the RCM method has been extensively covered by many authors such as Nowlan and Heap [8], Moubray [6] and Bloom [9]. The RCM method has many proponents but also received criticism. A point of concern raised by some is that the original RCM method is too costly to perform [10]. Hence, streamlined versions which simplifies one or more of the RCM steps have been proposed. Other authors, such as Moubray [11], however, argues against the effectiveness of such simplified versions of the method. The limited application of RCM on hidden failures is addressed by Rafiei, et al. [12]. Mokashi, et al. [5] mentions, amongst other issues, the lack of reliability data and FMEA from equipment suppliers as a barrier in the use of RCM. Despite these concerns the RCM method has since its introduction in aviation been used extensively and successfully in other industries, such as manufacturing and power generation [9].

In a marine context, RCM has been extensively used in the offshore oil and gas industry [9] and in naval forces, such as the US Navy and the British Royal Navy [6, 13]. Several classification societies are advocating the use of RCM on commercial cargo ships and some offer RCM analyses as a service to maritime customers, such as Lloyd's Register, DNV GL and Bureau Veritas. ABS [14] explains that RCM can improve equipment and system reliability and has published a comprehensive guidance note on RCM for use on commercial cargo ships. Despite the successful implementation in other maritime industries, RCM has not yet gained traction in the commercial maritime transport industry [15]. According to Mokashi, et al. [5], there are several reasons for this, but most stem from the relative uniqueness of each commercial ship design, making it necessary to conduct the resource-intensive RCM analysis separately for each ship and system. Commercial cargo ships are often one-off designs or part of a small series of sisterships which can still have considerable differences in machinery equipment and systems. Therefore, in most cases RCM analysis for one ship cannot be directly used for another ship.

RCM's lack of implementation in the maritime transport industry seems to mostly result from resource and cost issues and not applicability, and a number of studies explore the use of the method or parts of the method on commercial cargo ships. Lazakis, et al. [16] develop a holistic maintenance strategy to increase the operational reliability of ships in which RCM principles are utilised. Conachey, et al. [17] examine the use of ABS guidance notes [14] on RCM to improve reliability of machinery systems and to fulfil certain machinery survey requirements. Mokashi, et al. [5] conduct an in-depth analysis of the use of RCM in commercial maritime operations and conclude that the method has the potential to increase reliability and reduce maintenance costs but also identify problems specific to commercial ship operation that may hinder its practical implementation. Mokashi, et al. [5] also note that most attempts to implement RCM on cargo ships have so far been done by shore-based consultants or academics.

Some work has also been done on the use of the RCM method on autonomous and/or unmanned systems, mostly relating to aircrafts. Martinetti, et al. [18] create a framework for a scalable maintenance program for an unmanned aircraft system based on the RCM method. Walker [19] uses the principles of RCM to define the requirements for a real-time prognostics and health monitoring system for an unmanned aircraft.

A few studies have been done in the specific field of autonomous and/or unmanned ships. Jacobsen [20] uses RCM principles to identify barriers in the design of machinery systems on commercial cargo ships. The focus of the analysis is on how the maintenance tasks implemented for manned vessels today can be done on UMS. New issues arising from unmanned operation, however, are not specifically addressed. Sjøholt [21] uses RCM to construct a maintenance program for an autonomous and unmanned passenger ferry in the Trondheim harbour. The analysis offers insights into some fundamental questions of unmanned operation, but as the ferry is very small with electric propulsion and a short operation range, the findings relating to reliability issues for machinery systems have limited application to large commercial vessels. Rødseth and Mo [3] propose a novel maintenance concept suitable for unmanned shipping which is inspired by and includes elements of the RCM method.

RCM has the potential to be a valuable method in the assessment of maintenance needs and reliability issues on UMS. However, as in all applications, there are specific operational challenges of unmanned operation that affect the applicability of the RCM method. So far, there has been no examination of the RCM method when used on UMS nor an investigation of how potential challenges can be solved. Hence, the objective of this paper is to explore and address this issue by: (i) analysing the applicability of the RCM method in the examination of reliability and maintenance of machinery systems on large commercial cargo ships operating without a crew onboard for long periods at a time; (ii) proposing amendments to the RCM method to improve the examination of reliability and maintenance issues on unmanned cargo ships; and (iii) verifying the amended method in a case study through the analysis of a real machinery system.

2. Methodology, important concepts and data collection

This section describes the RCM methodology used in the present paper and introduces the most important concepts. Definitions of reliability and risk are explained, the concepts of systems and maintenance are briefly introduced and the relation between maintenance and reliability is described. The concept of the UMS in the context of this paper is also introduced. Lastly, the data used in the analyses and the method used for collecting this data are presented.

2.1. The RCM methodology

The development of the RCM method is generally credited to Nowlan and Heap [8] in their work on optimising maintenance management and improving reliability in the commercial aviation industry. The RCM method is typically described through seven basic questions about the asset or system [6, 9]:

1 Functions and Performance Standards - What are the functions and associated performance standards of the equipment in its present operating context?
2 Functional Failures - In what ways does it fail to fulfil its functions?
3 Failure Modes - What is the cause of each Functional Failure?
4 Failure Effects - What happens when each failure occurs?
5 Failure Consequences - In what way does each failure matter?
6 Preventive tasks - What can be done to prevent each failure?
7 Default Actions - What should be done if a suitable preventive task cannot be found?

Literature for the RCM method used in this paper is taken from Moubray [6], Bloom [9] and ABS [14]. The analysis in this paper follows the structure of the seven questions or steps described above, with some amendments, as presented in Section 3.

2.2. Concepts used in the present analysis

2.2.1. Reliability

Reliability is the probability of non-failure over time [22]. Some types of equipment will fail less often and are therefore more reliable than other. Reliability may be expressed in terms of a failure rate, i.e., failures per unit time. The failure rate does not reveal when a failure will occur, and reliability is therefore inherently coupled with uncertainty. Uncertainty is an obvious challenge in regard to machinery systems which must be designed with some resilience towards the effect of failures. Uncertainty also poses a challenge to maintenance planning where flexibility must be allowed to accommodate for unforeseen failures.

2.2.2. Risk

Failures are rarely of interest without an assessment of consequences. The product of probability and consequence is risk [14] or as defined by the International Organization for Standardization; the *"effect of uncertainty on objectives"* [23]. Risk can relate to consequences to human health and safety, operational delays and system availability, negative environmental impact, economic losses, etc. In this paper, risk is related to failures of machinery. Risk of failure to machinery is, at least from the perspective of system owners and operators, an undesirable but unavoidable attribute of the operation of machinery systems. Less risk is better, but risk reduction typically comes at a cost. There is no universal standard for which level of risk is acceptable, it depends on the situation and must be defined by the user [6]. In general, the risk relating to failure of machinery systems can be reduced either by improving the reliability of equipment units and/or preventing or mitigating the consequences of the failures.

Similar to risk, the term criticality can be defined as the product of probability and consequence [24]. Criticality is sometimes used instead of risk, synonymous to risk or as a measure of risk when it is related to failure modes, failure of components and its effects [14, 24]. Confusingly, criticality is sometimes regarded as a subset of risk and in other contexts risk is regarded as a subset of criticality [25]. The possible differences in meaning between criticality and risk in different contexts is recognised but it has not been found necessary to distinguish between the two terms in this paper. Hence, the term risk is used throughout the text to describe the product of probability and consequence.

2.2.3. Systems

A system can be broadly defined as an assemblage or combination of elements or parts forming a complex or unitary whole. In the context of this paper, a system is a machinery system, such as a lubrication oil system or a cooling water system. The machinery systems are composed of equipment units with one main function such as a pump or compressor [26, 27]. The case study presented in this paper is an analysis of a machinery system, namely a low-temperature cooling water system.

2.2.4. Maintenance

Maintenance can be defined as a *"combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function"* [24]. Maintenance can be divided into two main groups: preventive maintenance which is carried out to prevent a failure from occurring and corrective maintenance which is carried out to correct a failure after it has occurred.

Preventive maintenance includes both predetermined maintenance where tasks are carried out at a predetermined interval and condition-based maintenance [24]. In condition-based maintenance, tasks are carried out based on the assessment of the condition of the equipment unit through inspection, testing and analysis. A further subset of condition-based maintenance is predictive maintenance where the useful end life of the equipment unit can be estimated through repeated or continuous condition measurements in combination with known parameters about the degradation of the unit.

Predetermined maintenance is a very simple and cost-effective strategy for parts or units with an established correlation between wear and operating or calendar time. However, for some parts this correlation does not exist, and failures will occur at seemingly random intervals [28].

Condition-based maintenance is already used for CS today. For condition monitoring to be effective there must be one or more measurable potential failure "indicators". Much of the condition monitoring consists of low-level jobs, such as visual inspections and simple operational checks. More advanced tasks, such as partial disassembly of equipment units for inspection and measurements, megger testing of electrical resistance, thermography of electrical installations, vibration monitoring of bearings etc., are typically also part of the existing maintenance schedule. On larger equipment units, such as main engines, boilers and generators there will typically be continuous online monitoring of bearing temperature and lube oil pressures at various subcomponents etc. which are used as "failure indicators".

The benefits of condition-based and predictive maintenance are obvious, since performing maintenance when a potential failure is approaching better utilises the remaining useful life of the equipment unit. When failures can be predicted, shutdowns can be planned with as little disruption to the operation as possible and collateral damages due to failures can be avoided. However, condition-based, and predictive maintenance is not possible or technically feasible for all equipment units or parts [9]. Not all failures have measurable indicators and some failures progress so rapidly that failure detection is not practically feasible. There is a cost related to each failure mode with a corresponding measured indicator. If the measurement data is to be transmitted via satellite ashore and processed by a third party for predictive maintenance this will typically incur an additional cost. For many non-critical smaller equipment units, condition-based maintenance will not be cost effective and a deliberate run-to-failure strategy or is often chosen if predetermined maintenance is also not an option [6]. For small equipment units which provide an output essential for other larger processes, complete stand-by redundancy of the unit is often used as a strategy to avoid operation stops.

Maintenance can reduce risk by either decreasing the probability of the failure occurring or by limiting the consequences of the failure if it does occur. Preventive tasks of the machinery system will reduce the probability of a failure occurring but generally have no impact on the consequences of failures [14, 29]. Corrective maintenance tasks can reduce the consequences by restoring the functions of the failed equipment units and prevent cascading effects at a system level. Since corrective maintenance is done after a failure has occurred it will not have any impact on the probability in the period leading up to the failure. However, the work done to correct the failure may change the probability of failure after the corrective maintenance actions.

2.2.5. Operational scenario

Several different standardised definitions of unmanned and/or autonomous ships exists, see e.g. IMO [30], Lloyd's Register [31] and Rødseth and Nordahl [32], but none are yet uniformly recognised within the industry. Common for these definitions is that they focus primarily to the navigation and collision avoidance ability of the ships and tell very little of the automation level and ability of the mechanical systems. As the focus of this work is on the ships machinery systems the use of any of the standardised definitions has not been found sufficiently detailed. Instead the operational scenario is described in the following.

The concept of UMS used in the present paper follows that of the MUNIN project as detailed by Rødseth and Tjora [33]. During normal operation at sea, the cargo vessel is unmanned but may have the option to accommodate a crew during sea passages in certain situations. Since the vessel must be capable of unmanned operation, however, the analyses in the present paper are done based on the assumption of the cargo ship being unmanned at sea. All maintenance must therefore be done when the vessel is in port. During normal operation, the onboard control system is capable of operating the machinery systems within predefined boundaries without human control. One or more shore control centres continuously monitor the UMS remotely and can take over control of the cargo ship and its systems at any time. If the predefined limits of the control system are exceeded, a shore control centre will be prompted to take over control. It is assumed that all the equipment in the ship's machinery systems can be remotely operated and monitored onshore in the same way as from the ship's engine control room onboard a conventionally manned cargo ship.

2.3. Data and data collection

To evaluate and amend the RCM method, a case study on a cargo ship's machinery system was performed. For the case study, descriptions and diagrams of the analysed system were needed along with quantitative reliability data. The expert knowledge about the operation and maintenance of commercial cargo ships and related systems, as well as the RCM method, is mainly based on the engineering and system knowledge of the authors and a working group consisting of four participants from Kongsberg Maritime. The corresponding author has domain knowledge as a marine chief engineer responsible for operation and maintenance of technical marine systems with seven years of experience. Input to the practical application of RCM in a maritime context comes from the participants from Kongsberg Maritime, who have expert knowledge of system design, RAMS & FMEA and Regulatory Compliance and Safety. Four meetings were held during the autumn of 2019 where the methodology and results were discussed and evaluated.

The descriptions, diagrams and information about the analysed system were generously supplied by Kongsberg Maritime. Unfortunately, no data has been available for the reliability of the specific installation onboard the ship. In general, very little reliability data is available for marine systems. Therefore, the data used in the paper has been collected from the Offshore and Onshore Reliability Data (OREDA) handbook [27]. The OREDA handbook is one of the main sources of reliability data in the Oil and Gas industry [34]. While not completely identical, marine systems and the way the systems are operated on a cargo ship do not significantly differ from an offshore installation. The exposure to the hostile environment of corrosive seawater and salty sea air is comparable between offshore installations and ships. Machinery systems of both offshore installations and cargo ships are enclosed in compact metal structures subject to heat and vibration. Both offshore installations and ships are generally self-contained units producing their own power and relying on their onboard crew for operation, maintenance and emergency response. Ships are more mobile than offshore installations both geographically and regarding motions in the sea, but this is not believed to make a substantial difference in the context of machinery reliability.

The OREDA data is gathered from running systems and thus gives a "realistic" non-idealised picture of which failures the equipment units experience and how often. Data is typically gathered over a period of two to four years and usually excludes the beginning and end of component life [27]. Failure rate distributions from the OREDA handbook are assumed to be constant over the life of the equipment. The systems from which the OREDA data is gathered are maintained and the effect of the maintenance tasks on reliability is implicitly included in the failure rate values. However, no information about the maintenance tasks and intervals is available. It must also be noted that reliability data is aggregated from many different similar but not identical equipment units from several different installations and companies with different maintenance management systems.

Maintenance schedules and histories have not been available for the specific installation in the case study. Instead, maintenance data from four commercial cargo vessels has generously been made available by the Danish shipping company Lauritzen Kosan. The maintenance schedules and records from Lauritzen Kosan are used as a reference for which maintenance tasks would typically be carried out and at which intervals for a machinery system similar to that of the case study in this paper. The Lauritzen Kosan ships and machinery systems are slightly larger than the vessel used in this analysis but are otherwise comparable in functionality and layout. Details of the maintenance tasks are presented in Section 4.5.

3. Proposing amendments to the RCM method for UMS

Since the introduction of the RCM method in the aviation industry, there have been many different adaptations and versions of the method in order to meet the particular constraints and requirements of other applications [9]. The overall steps of the method, as described in Section 2.1, might remain the same, but the details of each step may change for different implementations. In this section, the applicability of the RCM method when used to evaluate maintenance needs and reliability issues on UMS is analysed and amendments to the method are proposed. In Section 3.1, the RCM method is analysed using CS as a reference through each of the seven steps of the RCM method as described in Section 2.1. Based on this analysis, amendments to the RCM method are proposed in Section 3.2.

3.1. Analysis of the differences and similarities between CS and UMS

3.1.1. Step 1 - Functions and performance standards

The definition of Functions and Performance Standards mostly depends on the physical systems under analysis, the equipment units that make up the systems and the operational situation under which the system is expected to perform. Some systems, such as the sewage system, may not be needed on a UMS depending on the operational scenario. Other systems or units, such as telecommunication and remote actuators will be required on a UMS to a greater extent than a CS. Systems such as the cooling water systems will be needed regardless of the presence of an onboard crew, and the primary function of providing a flow of water for cooling, for example, is not likely to change.

Many of the so-called secondary functions such as structural integrity, containment of liquid and safety functions of the systems will also be the same, but some might differ. On a UMS, the noise level, for example, might not be of any concern whereas remote monitoring and remote operation capabilities, for example, will be critical.

The Functions and Performance Standards completely depend on which system is being analysed and, equally important in this case, under which operating conditions the system will be running. It is important that all the possibilities and limitations that unmanned operation entails are thoroughly considered from the beginning of the analysis. The CS is a good starting point, but the systems on these cargo ships, and the existing maintenance schedule designed for these, are designed based on assumptions about failure detection, accessibility and manual intervention, which affects the possibility of performing corrective maintenance and which might be drastically different on a UMS.

3.1.2. Step 2 & 3 - Functional Failures and failure modes

Functional Failures, and by extension Failure Modes, are directly related to the specified Functions and Performance Standards and relate to the physical equipment units in the system. If the definitions of functions change so will the Functional Failures and the related Failure Modes.

3.1.3. Step 4 - Failure Effects

The physical Failure Effects can initially be expected to be very similar for CS and UMS, as there will not be any differences in how the equipment unit fails. However, how the failure is detected and the possibilities of performing corrective maintenance during operation will vary greatly depending on the presence of an onboard crew. In the description and evaluation of Failure Effects, careful consideration must be made for the likely restricted possibilities of failure detection and repair of the UMS while at sea. The longer the ship is inaccessible, the more time is available for a potential failure to develop from insignificant to critical. Detecting potential failures is critical in avoiding or limiting Failure Consequences but detecting a failure once it has happened will not help if nothing can be done to stop it. The length of the voyage also increases the probability that failures will occur in multiple equipment units in systems with redundancy.

3.1.4. Step 5 - Failure Consequences

When a failure occurs, the outcome depends on the possibilities for corrective maintenance tasks, and therefore the Failure Consequences can be expected to be significantly different from CS to UMS.

For some Functional Failures which would harm or endanger the onboard crew, such as a main engine crankcase explosion or accidental release of CO_2 into the engine room, the immediate consequences for human life can be expected to be much lower on the UMS since there is no one onboard during the voyage. Removing humans from the cargo ship, however, does not mean removing the risk to human life altogether. Repair crews must come onboard to maintain the ship's systems during port stays if maintenance cannot be done at sea. The risk to human life may therefore move from sea to port and cannot be expected to disappear entirely from the UMS because the occurrence of some work-related accidents is likely to follow the maintenance tasks.

For many Functional Failures, the Failure Consequences on UMS may be higher since there are no people present to return the equipment unit or system into an operational state. Failures which result in operation stops are particularly critical on UMS, since the corrective maintenance action that is possible on a UMS is very limited until it can be accessed by repair personnel. If failures critical to the propulsion of the vessel cannot be repaired, the UMS may be left "dead in the water" with major economic and safety consequences as a result.

3.1.5. Step 6 - Preventive tasks

No amendments to the decision logic used for maintenance task selection, such as that of ABS [14] used in the case study in the present paper, is found to be needed for the application of RCM on UMS. The result of applying the decision logic may, however, be very different between a UMS and a CS if the risks related to the potential failures differ. If the risk is found to be higher due to the cargo ship being unmanned, more Preventive Tasks may need to be assigned to reduce the probability of failure. Condition based maintenance is still preferable whenever technically feasible. Unmanned operation is, however, likely to affect the possibilities for doing certain condition monitoring tasks as described in Section 2.2.4 and further discussed in Section 5.2. The breakeven point of when a condition monitoring task is cost effective is also likely to change since the strategy of run-to-failure followed by corrective maintenance cannot be relied on to the same extend as on a CS.

Maintenance on a UMS can only be done during port stays instead of throughout the operation of the vessel. The infrastructure for maintenance support from shore might not be available in all ports. It is also likely that the cost and quality of maintenance support from external contractors will vary from port to port. If inhouse maintenance support is used it is likely that ship operators will want to concentrate their resources in a few centralised locations. Because of this it might be necessary or preferable to concentrate more maintenance tasks into a few concentrated maintenance campaigns in specific ports rather than doing maintenance at each port of call. Since the main purpose of port calls is the loading and unloading of cargo, the operation will also put constraints on which machinery systems can be maintained. Some systems may only be accessible during either loading or discharging. Others, such as ballast water systems which are used both during loading and discharging, might not be accessible without interfering with port operations. These operational constraints along with the need for doing more maintenance tasks simultaneously within a confined space and time will require more detailed maintenance planning.

The possibility of performing Preventive Tasks on a UMS, however, is not expected to very different than on a CS. Preventive Tasks are by nature planned tasks which for most ships would be possible to plan and carry out during port stays. However, some compromises between the wish to extend maintenance intervals to achieve maximum useful life of an equipment unit or part and the need or wish to concentrate maintenance tasks into fewer campaigns might have to be made. The intervals between periodic tasks on a UMS also naturally cannot be shorter than the voyage length of the vessel.

3.1.6. Step 7 - Default Actions

Where Preventive Tasks alone are not enough to reduce the risk to an acceptable level, or are not technically feasible, Default Actions must be taken. Default Actions can be "failure finding tasks", "redesign" or "no scheduled maintenance" [6]. Failure finding tasks are scheduled tasks aimed at determining whether a failure that does not in itself have an evident effect on the function of the equipment has occurred. Detection of failures while the vessel is underway can be expected to be more difficult on unmanned cargo ships in general. Since failure finding tasks are scheduled tasks, however, they can most likely be planned to be carried out when the UMS is in port. As with preventive tasks, the interval cannot be shorter than the voyage length for tasks which require human intervention. Operational testing of stand-by equipment may be possible to perform without a human presence depending on the remote operation and monitoring system employed. For evident failures where the risk cannot be reduced to an acceptable level, redesign is necessary.

3.2. Amending the RCM method to be used on UMS

The RCM method is at an overall level applicable for the use on UMS based on the analysis in Section 3.1, but some limitations were found.

Long periods of unmanned operation pose unique challenges for the assessment of reliability of machinery systems. System may be required to operate in a partially failed state for long periods of time without the possibility of repair and corrective maintenance. It is an assumption in the conventional RCM method that corrective maintenance actions are made in a "timely manner" [9]. If corrective maintenance actions can be made in a timely manner, a failure may not continue to develop in severity after detection and multiple failures in systems with redundancy of machinery are not likely to happen.

The aviation industry, where RCM originated from, and the nuclear power industry specify time envelopes within which the failure must be repaired to avoid the risk of additional failures. These time envelopes can be hours or days, airplanes can be grounded, and power plants can be forced to power down if they are not met. Voyages of cargo ships, however, may last for weeks. On a CS it is assumed that the onboard crew can carry out the majority of the corrective maintenance when the ship is at sea. Hence, even though it is possible to include the voyage length in an RCM analysis of a CS, the results will not change whether the voyage length is two days or two weeks. On a UMS, however, where the possibility for doing corrective maintenance at sea is severely restricted, the voyage length will have a huge impact on the result of the RCM analysis. On long unmanned voyages it will often not be possible to do corrective maintenance actions in the "timely manner" assumed in the conventional RCM method. Powering down a cargo ship in the middle of the ocean is likely to have significant economic and safety-related consequences and will rarely be a viable option. The amended RCM method must therefore specifically address the effect of long voyages on the failure development.

In the risk assessment in the RCM analysis, the initial evaluation is based on a scenario where no preventive maintenance tasks are carried out. It is important to remember, however, that this initial scenario already implicitly includes corrective maintenance tasks. Considerations on how failures are detected, how the consequences of failures can be

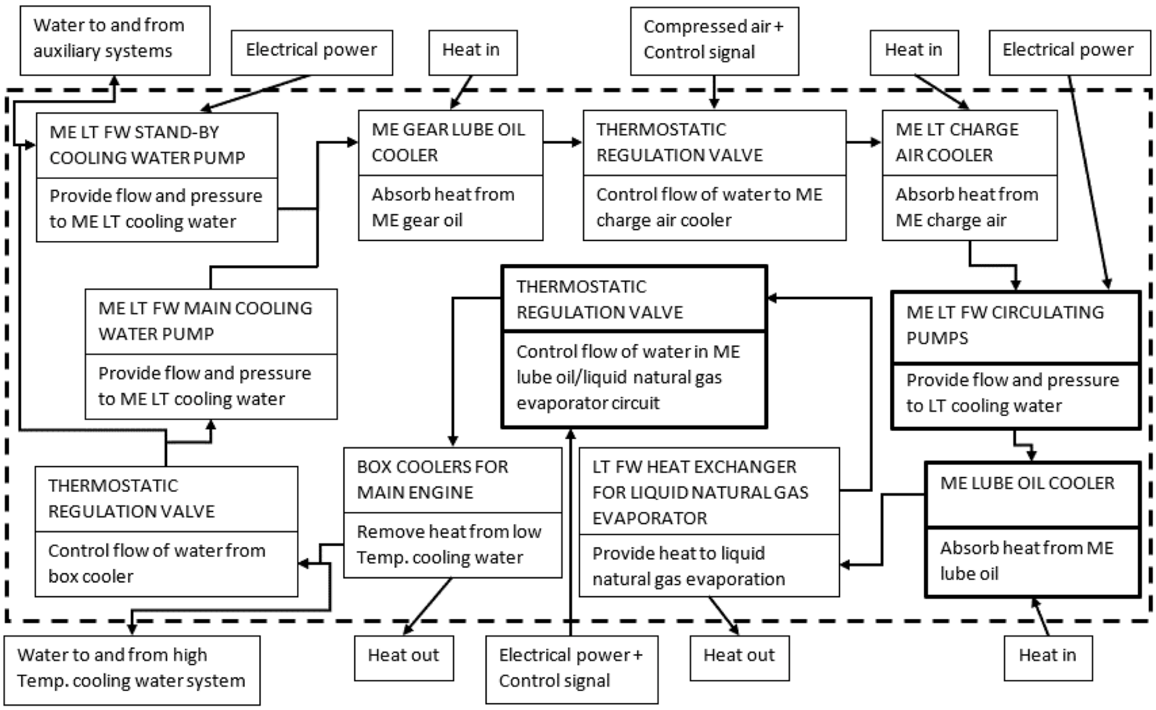

Fig. 1. Block diagram of Main Engine (ME) Low Temperature (LT) Fresh Water (FW) cooling water system.

mitigated until maintenance can be implemented and which corrective maintenance tasks are necessary to return the equipment unit to an operational state are included in the description of Failure Effects and Failure consequences. Corrective maintenance tasks are not isolated in the same way as the preventive maintenance tasks in the conventional RCM method and it is not always clear if the possibilities for corrective maintenance tasks adhere to the physical design of the system or the implicit assumptions about the operational situation. On a UMS, where the possibilities for corrective maintenance tasks are very different from conventional manned operation, the effects of both preventive and corrective maintenance tasks should be individually assessed. Hence, differences in the results between UMS and CS of the RCM analysis are likely, as shown in Section 3.1, and there is a need for adjusting and amending the RCM method. In particular, Step 4 - Failure Effects and Step 5 - Failure Consequences, the application of the conventional RCM method is found to be of limited feasibility when used on a UMS. For these two steps, the following amendments to the conventional RCM method are proposed in this paper:

Step 4 - Failure Effects: In the assessment of Failure Effects, consider and describe both Immediate and Long-term Effects separately.
Step 5 - Failure Consequences: (i) make risk assessments specific to the intended voyage length. If the voyage length is not known precisely, make multiple risk assessments with different voyage lengths; (ii) make separate risk assessments showing the effects of preventive maintenance tasks and corrective maintenance tasks distinct from each other.

4. Applying the amended RCM method in a case study

In this section, a real machinery system is analysed using the amended RCM method proposed in Section 3. The seven steps of the RCM method are applied to the case study using the structure from the ABS Guidance Notes [14], but with the proposed amendments. The analysis is carried out for two situations: one where the cargo vessel is conventionally manned and one where it is unmanned. Due to the proposed amendments to the RCM method, the unmanned situations are further sub-divided into a short (UMS Short) and a long voyage (UMS Long) situation. A short voyage in this case is one day in duration and as an example of a long voyage a duration of fourteen days is used. The analysis explores the extent to which a maintenance strategy for a CS can be used on a UMS. Changes to the maintenance schedule and the design of the machinery system on a UMS are proposed where necessary.

4.1. Step 1 - Functions and performance standards

4.1.1. Systems and boundaries

The cargo ship is approximately 75 metres in length with one main engine of about 2400 kW powered by Liquified Natural Gas (LNG) for propulsion. The system chosen for the analysis is the Main Engine (ME) Low Temperature (LT) Fresh Water (FW) cooling water system which provides cooling for the ME lube oil cooler, ME gear lube oil cooler and ME LT charge air cooler as well as providing heat for the evaporation of the LNG fuel. An overview of the ME LT cooling water system can be seen in Fig. 1. The system was chosen because it is a relatively simple system and relatively self-contained while simultaneously being critical for the operation of the vessel. If the LT cooling water system fails, the main engine will not be cooled, and it will shut down very quickly. In the setting chosen for this analysis, the main engine is the only source of propulsion, which is representative of a major portion of large ocean-going cargo vessels in operation today.

The system under analysis is designed for conventional manned operation. When analysing the system under unmanned operation, the capabilities of the UMS, as described in Section 2.2.5, are assumed but some additional assumptions must be made to make the comparison realistic. It is assumed that all valves that can be operated manually in the existing system can be remotely operated on the UMS. Some form of remote visual monitoring by cameras is also assumed. It is outside the scope of this paper to design the remote control and monitoring systems needed for unmanned operation. The increased complexity and possible new sources of failure that these systems introduce cannot be accurately assessed based on the available material and are therefore not evaluated in the analysis.

Function item no	Function statement	Function type	Functional failure item no	Functional failure statement
B.1	Provide heat transfer of not less than 1270MJ/h	Primary	B.1.1	Critically fail to provide heat transfer

Failure mode item no	Failure Mode	Evident/hidden	Failure mechanisms	Failure characteristics
B.1.1.1	Insufficient heat transfer	Evident	Unknown	Wear-in Random Wear-out

Local effect	System effects Immediate	System effects Long term
No cooling of ME lube oil	Loss of cooling to ME lube oil, high lube oil temp, ME slowdown, eventually ME shutdown, complete loss of propulsion	Unknown

Corrective measures	Failure detection
Loss of propulsion until function is restored	ME lube oil temp high alarm, ME slowdown alarm, ME shut-down alarm

Fig. 2. An example of the analysis of one Failure Mode of the ME lube oil cooler.

The system boundary is shown in the block diagram in Fig. 1. Arrows inside the system boundary indicate the LT water flow in a simplified manner. There are more flow paths of the LT water than shown in Fig. 1, but all heat exchangers are critical to the operation of the main engine, and by extension so are all the pumps and regulation valves. A failure anywhere along the simplified flow path will affect the propulsion. The analysis focuses on the physical operations and physical failures of the equipment. Instrument and control failures are only assessed if they impact the operation of the physical equipment.

It is evident from the System Block Diagram in Fig. 1 that the system only consists of three different equipment unit types: pumps, heat exchangers and thermostatic regulation valves. The pumps are configured two-and-two, one providing stand-by redundancy for the other in two comparable pump sets. All equipment units are critical, as the failure of any of them can limit or stop the output of the system and by extension the propulsion.

There is not enough detail in the available material to differentiate one equipment unit from another of the same type with regard to reliability data. The RCM analysis, and most importantly the risk assessments, for similar equipment units will therefore be based on the same OREDA reliability data. The analysis of one equipment unit will be valid for all the equipment units of the same type. Because of this, only three equipment units are analysed: the ME LT FW circulating pumps, the ME lube oil cooler and one thermostatic regulation valve.

With the System Block Diagram in Fig. 1 as a guide, Functions and Performance Standards of each of the system's individual parts are described for the three equipment units, an example of which can be seen in Fig. 2.

4.1.2. Consequence setting

The consequence setting chosen for the analysis is "likely consequences", as opposed to "worst case consequences". Shipping is a safety-orientated business, but it is also a highly competitive business with small profit margins. Safety comes at a cost and must be balanced with revenue. Proposing a system that can deal with all conceivable failures will not be beneficial for a real-life application.

4.1.3. Operational boundary

Based on an initial analysis, a decision was made to focus on the consequences of failures to the propulsion of the vessel. There are no failures in the LT water system that are likely to have a direct impact on the environment. The LT water system is a low-pressure system that does not contain fluids or materials that are poisonous nor is it likely to cause serious harm to people in case of failure, and safety-related consequences are therefore limited. Some damage to equipment can be caused by failures but the magnitude of this damage is limited compared to the operational consequences. Failures to propulsion could of course lead to groundings, collisions or other dangerous situations at sea, but those situations should be examined in a risk analysis with the loss of propulsion as the hazardous event, instead of as a failure consequence as in this RCM analysis. The setting chosen in this case study is one where a failure of propulsion only has operational consequences which would translate to the cargo vessel being in open sea, in fair weather, with no immediate danger of collision or grounding.

4.1.4. Failure distribution

In the assessment of risk, a constant failure rate distribution is assumed for all equipment units following the practice of the OREDA handbook as described in Section 2.3. The most important implication of this is that failures are considered to happen purely at random and completely independent of the age of the item [27].

4.2. Steps 2 & 3 - Functional failures and failure modes

With the System Block Diagram in Fig. 1 again as a guide, Functional Failures are now designated for each Function described in Step 1 and one or more Failure Modes are further assigned to each Functional Failure. Failure Modes are all events that are reasonably likely to cause the Functional Failure [6]. The Failure Modes used in this analysis are the Failure Modes described in the OREDA Handbook [27]. Using the standard Failure Modes enables direct use of the failure rate data given for these in the OREDA handbook.

Failures and Failure Modes in the OREDA handbook relate to a failure of any of the required primary or secondary functions of an equipment unit. The failure of a safety function or an instrument for monitoring operational parameters can result in increased operational risk, and a sensible response would be to immediately stop the operation of the unit, but it does not necessarily impact the primary function of the

Long term loss of propulsion	Critical	4				High Risk	
Short term loss of propulsion	Significant	3		Medium Risk			
Reduced propulsion power	Moderate	2					
Propulsion is not affected	Minor	1	Low Risk				
Consequence			1	2	3	4	5
			Improbable	Remote	Occasional	Probable	Frequent
		Probability	Fewer than 0.001 event/year	0.001 to 0.01 event/year	0.01 to 0.1 event/year	0.1 to 1 event/year	1 or more event/year

Fig. 3. Risk Matrix for loss of propulsion.

unit directly. In this case study, only those Failures Modes that directly impact the primary function of a unit are considered.

An example of the analysis of one Failure Mode, “Insufficient heat transfer”, for the ME lube oil cooler is shown in Fig. 2. There are 10 Failure Modes for the ME lube oil cooler and 29 Failure Modes in total for the three analysed equipment units. An analysis is made for each of the identified Failure Modes as shown in Fig. 2.

4.3. Step 4 - Failure Effects

Next in the analysis, the effects of each failure are described and divided into Local Effects and System Effects. A Local Effect is the direct consequence of the failure of the equipment unit such as leakage of oil, damage to bearings etc. A System Effect could be the loss of water pressure in a cooling water system.

Based on the amendments to the RCM method described in Section 3.2, the System Effects are subdivided into Immediate Effects and Long-term Effects. For this case study, immediate System Effects are defined as those where detection and intervention cannot be reasonably expected before the consequence occurs. In the case of control failure, for example, or the blowout of a gasket, the effect will be sudden and there will be little chance to prevent or limit the effects of the failure. Long-term Effects are those that accumulate over time after the failure occurs. A minor leak of lubrication oil from a LT freshwater pump bearing housing, for example, will not have any System Effects before the lubrication stops, the bearing breaks down and causes the shutdown of the pump. The System Effects will entirely depend on the possibility of detection and intervention after the occurrence of the Functional Failure.

4.4. Step 5 - Failure consequences

In this analysis, the assessment of risk is conducted using a risk matrix as seen in Fig. 3. The risk matrix is based on the ABS Guidance Notes [14] but has been constructed specifically for this analysis. There is no risk matrix that fits all types of risk analyses, so an important prerequisite is to define it specifically for the system at hand [35].

The layout of the risk matrix in Fig. 3 has been discussed with and approved by Kongsberg Maritime during one of the work group meetings described in Section 2.3. The probability categories are identical to those of the ABS guidelines, but the consequence category descriptions are adapted to suit the specific implementation of this case study and the amendments to the RCM method proposed in Section 3.2.

A risk level of Low, Medium or High is determined as a result of the probability and consequences for each Failure Mode of the three analysed equipment units using the risk matrix in Fig. 3. The probability of each Failure Mode occurring is obtained from the OREDA handbook. The assessment of the consequences of each Failure Mode is based on the Local Effect and System Effects described in Section 4.3, which in turn is based on system and engineering knowledge.

Using the amendments to the RCM method developed in Section 3.2, the effects of preventive and corrective maintenance are separated into two separate scenarios. A third scenario including the effects of the proposed system redesign is also analysed, if applicable.

- Scenario 1: Preventive maintenance only
- Scenario 2: Preventive and corrective maintenance
- Scenario 3: After system redesign

The results of the assessment of risk for the three scenarios using the risk matrix in Fig. 3 are explained in Section 4.7 and presented in Figs. 4 and 5 and in the Appendix in Fig. A.1.

4.5. Step 6 - Preventive tasks

The As Low as Reasonably Practicable (ALARP) principle is used for

		Scenario 1: Preventive maintenance only			Scenario 2: Preventive and corrective maintenance									Scenario 3.1: System redesign *Redundancy of heat exchangers*									Scenario 3.2: System redesign *Redundancy of heat exchangers & Double-wall heat exchangers*								
					Manned			UMS Short			UMS Long			Manned			UMS Short			UMS Long			Manned			UMS Short			UMS Long		
Failure Mode		C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R
Insufficient heat transfer	Critical	4	2	**H**	3	2	**M**	4	2	**H**	4	2	**H**	2	2	**M**	2	2	**M**	2	2	**M**	2	2	**M**	2	2	**M**	2	2	**M**
External leakage - process medium	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
External leakage - utility medium	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
Internal leakage	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**	3	1	**M**	4	1	**M**	4	1	**M**
External leakage - process medium	Degraded	4	3	**H**	1	3	**L**	1	3	**L**	4	3	**H**	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**
External leakage - utility medium	Degraded	4	3	**H**	1	3	**L**	1	3	**L**	4	3	**H**	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**
Internal leakage	Degraded	4	3	**H**	1	3	**L**	1	3	**L**	1	3	**L**	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**
Plugged/Chocked	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
Structural deficiency	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
Structural deficiency	Degraded	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**

C = Consequence *L = Low*
P = Probability *M = Medium*
R = Risk *H = High*

Fig. 4. Risk assessment of Heat Exchanger.

		Pumps			Lube oil cool.			Reg. Valve		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Manned	Scenario 1: Preventive maintenance only	73	13	13	0	10	90	33	17	50
	Scenario 2: Preventive and corrective maintenance	**80**	**20**	**0**	**40**	**60**	**0**	**50**	**50**	**0**
	Scenario 3: System redesign	93	7	0	40	60	0	100	0	0
UMS Short	Scenario 1: Preventive maintenance only	73	13	13	0	10	90	33	17	50
	Scenario 2: Preventive and corrective maintenance	**80**	**13**	**7**	**30**	**10**	**60**	**50**	**17**	**33**
	Scenario 3: System redesign	93	7	0	0	100	0	100	0	0
UMS Long	Scenario 1: Preventive maintenance only	73	7	20	0	10	90	33	17	50
	Scenario 2: Preventive and corrective maintenance	**80**	**7**	**13**	**10**	**10**	**80**	**50**	**17**	**33**
	Scenario 3: System redesign	93	7	0	0	100	0	100	0	0

Fig. 5. Summary of risk levels for all three analysed equipment units. Numbers in pct. of total failure modes.

Table 1
Preventive maintenance tasks for LT Cooling Water system (from Lauritzen Kosan data).

Job name	Interval	Job description
Cooling System Test	1 week	Testing of chemical properties of LT water. Chemical dosing is adjusted based on findings
Manual Opening & Closing of LT Cooling FW 3-Way Valve	1 month	Functional testing. Ensure that valve can operate over the full range of opened to closed
ME LT FW Stand-by Pump Routine	1 month	Failure finding task. Check that pump is able to start and provide pressure. Visual check of general condition of pump as well as check for leaks, vibration and noise.
Visual inspection of Rubber Bellows	3 months	Visual inspection for general condition and leaks.
Cooling Water Tank Check for Normal level	3 months	Visual inspection of level of tank
ME LT FW Stand-by Pump Maintenance	6 months	Intrusive testing. Check for electrical resistance of motor. Turn shaft by hand to check rotational resistance
Check of thermostatic valve	12,000 h	Intrusive testing. Ensure that valve functions as calibrated. Recalibrate or replace if necessary
Engine driven cooling water pump overhaul	18,000 h	Intrusive maintenance. Disassemble pump and replace worn out parts
Thermostatic element replacement	36,000 h	Intrusive maintenance. Replace thermostatic element

determining the applicability of preventive maintenance tasks and/or default actions.

For Failure Modes with a broadly acceptable risk level (low in Fig. 3), no Preventive Tasks or Default Actions are needed. If the risk level is in the ALARP region (medium risk in Fig. 3), Preventive Tasks or Default Actions must be assigned. For Failure Modes with risk level in the unacceptable region (high risk in Fig. 3), Preventive Tasks or Default Actions must be assigned until the risk level becomes acceptable.

There is not enough detail in the available material to propose maintenance tasks for the specific equipment unit analysed in this case study, which typically would be based on a decision logic diagram as described in Section 3.1.5. Instead, the maintenance data from Lauritzen Kosan as described in Section 2.3, and as can be seen in Table 1 is used here as a reference for which preventive maintenance tasks will typically be carried out on a system similar to the one analysed in this case study.

One out of the nine maintenance jobs in Table 1, “Visual inspection of level of tank”, can be performed remotely, as there is already an LT water tank level indicator installed in the system in the case study. One other job, “ME LT FW Stand-by Pump Routine”, can be partly completed as it is assumed that pumps can be started and stopped, and the pressure can be monitored remotely. All remaining tasks require human interaction to complete in the present design of the system. The intervals for all tasks except one are of one month or more and should be possible to carry out in port for the majority of ships. For the one task with an interval of one week, “Cooling System Test”, a more detailed evaluation should be done, but online monitoring of the cooling water quality may be possible. It is also possible, again based on a detailed evaluation, that the task interval can be extended without significant consequences.

Data on how many man-hours each job takes to complete is also recorded in the Lauritzen Kosan data. The total for the all the jobs done on the LT water system is 59.6 h in total for the four vessels during a 6-month period. This translates to only 2.5 h of maintenance work per vessel per month on average for the LT system, which should be possible to undertake during port stays. It must be remembered that the maintenance on the LT cooling water system is only a very small part of the total maintenance tasks required onboard the vessel.

It is assumed that the maintenance tasks and intervals listed here are similar to the level of maintenance done for the equipment units in the OREDA data [27]. The effect of the existing maintenance tasks in Table 1 on reliability is thus already included in the risk assessment using OREDA failure rate data. ABS [14] explains that for Failure Modes with the risk level “unacceptable”, maintenance alone is typically not enough to reduce the risk to an acceptable level. Additional preventive maintenance tasks or reduced maintenance intervals are therefore not sufficient, and a change in the system design is thus needed to achieve an acceptable risk level.

4.6. Step - 7 Default actions

For Failure Modes with unacceptable risk levels and where preventive measures are not sufficient to reduce the risk levels to an acceptable level, design changes need to be applied, and the risk level is evaluated again under the new conditions. If the design change does not reduce the risk level sufficiently, further design changes are applied in an iterative manner until an acceptable risk level is achieved.

4.7. Results of the case study

Maintenance tasks and intervals, which are normally the most important end result of an RCM analysis, do not differ much between UMS and CS in this case study. The salient results of the amended RCM method are found in the differences in the risk levels between manned and unmanned operation, which can be found in Fig. 4. Therefore, this section focuses on the risk levels, as well as the design changes which are proposed to reduce the risk for the unmanned cargo ships to acceptable levels.

Fig. 4 shows the detailed results of the analysis of the ME lube oil cooler. The detailed results of the other two analysed equipment units;

the ME LT circulating pumps and the thermostatic regulation valve, can be found in Fig. A.1 in the Appendix. A summary of the risk levels for all three equipment units analysed in this case study can be seen in Fig. 5.

4.7.1. The results of the analysis of the ME lube oil cooler

Fig. 4 shows the consequence severity, probability value, and the resulting risk level for each Failure Mode of the ME lube oil cooler. It also shows whether a Failure Mode is "critical", meaning that it will cause immediate loss of the equipment unit function, or if it is "degraded", meaning that it will result in reduced output of equipment function.

In Scenario 1: Preventive maintenance only, the consequences, probabilities, and resulting risk levels are the same for manned, UMS Short and UMS Long, and are therefore only shown once. In Scenario 2 and Scenario 3, the consequences, probabilities, and resulting risk levels vary greatly between manned and UMS Short and UMS Long, as seen in Fig. 4 and they are therefore shown separately.

Fig. 4 shows that the ME lube oil cooler has ten Failure Modes, each of which can cause degraded or a critical Functional Failure of the equipment unit. In Scenario 1: Preventive maintenance only, nine out of ten Failure Modes have a consequence severity "4, critical" and a probability of "2, remote" or "3, occasional", resulting in a high risk. There are four degraded Failure Modes, three of which are able to cause complete long-term loss of propulsion in Scenario 1: Preventive maintenance only. These three degraded Failure Modes are related to leakages. If a leakage from the ME lube oil cooler is left unattended, the system will eventually be drained of LT water or ME lube oil, causing loss of cooling or lubrication, resulting in ME shutdown. An internal leakage, if left unattended, can also result in severe damage to the engine and shutdown due to loss of lubrication. Detection of these leakages may be possible using camera surveillance or remote oil analysing systems. However, the possibilities for stopping or minimizing the leakages on a UMS at sea, even if detected, would be very limited.

In Scenario 2: Preventive and corrective maintenance, there are major differences between manned and unmanned operations. For manned operation, the risk levels of all the failures modes are reduced to medium or low. For UMS Short, there are still six modes with an unacceptable risk level of high and eight for UMS Long. The two additional Failure Modes with risk level high in the UMS Long situation compared to the UMS Short come from the matter of the degraded Failure Modes related to leakages. On long voyages, a non-critical leakage has a longer time to drain the system of oil or water, eventually causing complete loss of the equipment function.

A design change in the form of redundancy of heat exchangers is proposed to reduce the risk level for unmanned operation. Applying the first design change still leaves one Failure Mode with risk level high. For the Failure Mode "Internal Leakage", the damage occurs once LT water has mixed with the ME lube oil and it is not enough to stop the leakage only. As long as there is a substantial amount of water in the lube oil, damage will continue to develop for the engine bearings. Hence, to avoid water contamination of the ME lube oil in the heat exchanger a higher pressure is normally maintained on the ME lube oil than on the LT water. When the engine is not running, however, there will not be any lube oil pressure, but the LT water will still have a static pressure and a pressure from the circulation pump. Because the "Internal Leakage" of LT water into the ME lube oil can only occur during operation of the ME, the failure rate from the OREDA handbook [27] cannot be used directly. However, the Failure Mode "Internal Leakage" is still assumed to have an unacceptable risk level since it has a consequence severity of "4, critical". For the risk level to be reduced to medium, the probability of failure would have to decrease from "3, occasional" to "1, improbable" which is not assessed to be realistic for this Failure Mode.

It may be possible to detect an internal leak using remote oil analysis equipment but the possibilities for removing the water from the oil or replacing the oil remotely on a UMS at sea will be very limited. To eliminate or at least greatly reduce the possibility of internal leakage, it is proposed to use double-wall heat exchangers which have a void space between the process and utility medium. A leak of either cooling water or lube oil will run into the void space instead of contaminating the other medium, thus also enabling easier failure detection. The OREDA handbook [27] does not contain failure rate data specifically for double-wall heat exchangers. It is assumed that the probability of the Failure Modes related to external leakages is unaffected by this design change but that the probability of the Failure Mode "Internal Leakage" will be reduced to "1, improbable". The introduction of double-wall heat exchangers reduces the final Failure Mode risk level to medium.

4.7.2. General results for all three equipment units

Fig. 5 shows the risk assessments for manned, UMS Short and UMS Long for all three equipment units. The values in the table are percentages of Failure Modes with low, medium and high risk levels respectively, out of the total number of Failure Modes for that equipment unit. The ME lube oil cooler, for example, has ten Failure Modes in total. For "UMS Long" in Scenario 2: Preventive and corrective maintenance, the ME lube oil cooler has one Failure Mode with risk level low and one with risk level medium, equalling 10 per cent each. The last eight Failure Modes have risk level high, making up the remaining 80 per cent.

The summary of the risk levels in Fig. 5 shows the same general results as seen as in the detailed analysis of the ME lube oil cooler in Fig. 4. There is almost no difference in the risk level between manned and unmanned operation in Scenario 1: Preventive maintenance only. However, in Scenario 2: Preventive and corrective maintenance, there are major differences. While preventive and corrective maintenance is sufficient to reduce the risk level to low or medium for all three equipment units during manned operation, it is not enough to achieve an acceptable risk level for any of the three equipment units for unmanned operation. For the thermostatic valve, redundancy of the entire equipment unit is proposed. For the ME LT FW circulating pumps, an additional redundant pump is proposed. These design changes will reduce the risk levels to medium and low. The detailed analysis of the ME LT FW circulating pumps and the thermostatic valve can be seen in the Appendix. If the same design changes are applied to the manned situation as the unmanned situations, the risk levels will be as low or lower for manned operation than for unmanned operation

5. Discussion

In this section the results of the paper are discussed. The section is divided into four topics: in Section 5.1 the RCM method and amendments are discussed. Conventionally manned cargo ships vs. unmanned cargo ships are discussed in Section 5.2 and in Section 5.3 uncertainty is considered. Lastly, the discussion of maintenance of unmanned cargo ships in the future is presented in Section 5.4.

5.1. The RCM method and amendments

RCM is used in many industries, each of which have their specific characteristics and challenges regarding maintenance and reliability of machinery. Each industry will typically adapt the specific application of the method to suit their specific challenges. The amendments to the RCM method proposed in this paper are designed for use for the analysis of unmanned commercial cargo ships. What sets UMS apart from other industries is the operational constraint of not being able to access the machinery systems for repair of failures and performing maintenance for long periods at a time while at the same time not being able to power down the vessel without huge economic and safety-related consequences. This constraint also sets UMS apart from a CS that may otherwise be constructed in a similar manner. The proposed amendments to the RCM method focus on this difference in operational situations.

The amendment proposed in this paper to Step 4 - Failure Effects ensures that the long-term effects of the operation of a failed or partially failed system is considered when corrective maintenance actions cannot be performed in the timely manner otherwise assumed in the RCM method. In the amendments to Step 5 - Failure Consequences it is ensured that the intended voyage length is specifically considered. The voyage length will influence the probability of failure in multiple equipment units in systems with redundancy as detailed in Section 3.1.3 and in the Appendix. The voyage length chosen for the long unmanned voyage in the case study is fourteen days which is typical for trans-atlantic or transpacific passages. Many cargo ships have bunker capacity for much longer voyages and some cargo ships regularly do uninterrupted sea passages of three or four weeks. The method can be used for any voyage length and the amendments will ensure that the effects which the longer voyage will have on reliability is considered.

5.2. Conventionally manned cargo ships vs. unmanned cargo ships

The application of the amended RCM method to the case study shows that the main differences between manned and unmanned operation lie in the effect of corrective maintenance actions. For manned operation, corrective maintenance actions are able to reduce the risk level to an acceptable level for all Failure Modes for all equipment units. For the unmanned cargo ship, however, there are several Failure Modes with a risk level of high after the inclusion of the effect of corrective maintenance across all three equipment units.

Corrective maintenance tasks may be effective on UMS, but the main challenge is the severely restricted possibility of employing corrective maintenance actions. Most corrective maintenance actions rely on manual intervention at sea, which is not possible on UMS. If only preventive maintenance actions are possible, there are many Failure Modes with high risk levels for both manned and unmanned operation. For the ME lube oil cooler, eight out of ten Failure Modes have the potential to cause complete loss of propulsion and have a probability of failure in the category “4, probable”. If only preventive maintenance actions can be utilised, and if these only influence probability and not the consequences of a failure mode, the probability of failure has to be reduced by several orders of magnitude to result in an acceptable risk level.

In the case study, it was assessed that additional maintenance tasks beyond those described in Table 1 would not be sufficient to reduce the risk levels of any equipment unit from high to medium or low. This is perhaps a crude assessment, but there is a limit to how much impact maintenance can have on reliability. Maintenance can contribute to maintaining the level of reliability designed and built into the system, but the level of reliability can never be higher than that inherently provided in the system design [28] unless modifications to the design are implemented.

In the case study only the consequences of failures to the propulsion of the vessel is considered, as explained in Section 4.1.3. Failures of the LT water system analysed in the case study was evaluated to be unlikely to cause direct harm to human life, environment and equipment. In the analysis of other systems this will not be the case, but the amended RCM method can be used for the evaluation of these other type of consequences as well. It is further defined in the case study that a failure of the ship propulsion only has operational consequences, which is a limited assumption. Depending on the operational setting a failure of propulsion could further result in collisions with other ships or structures, groundings or foundering of the vessel. This could result in material damages, loss or danger to human life and environmental harm, all with potentially severe financial consequences as an outcome. Unmanned operation would certainly affect the magnitude of these consequences. Exactly how is still very uncertain and it is outside the scope of this paper to make a quantitative evaluation of this. Some reflection can be made on the topic, however.

In a collision, allision, grounding or foundering following a loss of propulsion, the consequences for human life could, because there are no people on board during sea passage, be expected to be less on a UMS, at least initially. Except in the case of the complete disappearance of the vessel in deep water, however, the ship would need to be salvaged which would most likely require human interaction. Without an onboard crew, mitigating the consequences of accidents would be more difficult [36] resulting in more severe environmental and material damages. The frequency at which marine accidents occur may decrease, however, due to an expected reduction in human errors during operation [36]. Human error which is an important contributing factor in many maritime accidents, will not disappear with unmanned operation [37, 38], but its nature may change. For the specific case study in this paper unmanned operation may not have a significant impact on human errors related to maintenance, since maintenance must still be carried out manually by repair personnel in port. Unmanned operation will, however, have a large impact on the ability to carry out corrective maintenance during operation.

5.3. Uncertainty

The analysis in the current paper shows that it is problematic to use existing machinery systems on UMS due to poor reliability and the severely restricted possibilities for performing corrective maintenance during unmanned operation. It must be remembered, however, that the analysed system was designed for manned operation and that it may not be suitable for unmanned operation, because it is not designed for this.

The OREDA database [27] shows that the ME lube oil cooler has high failure rates across the different Failure Modes. For this specific equipment unit, it seems very unlikely that preventive maintenance will be able to sufficiently reduce the probability of failure to achieve an acceptable risk level. For the pumps, and also for the regulation valve to some degree, it is possible that preventive maintenance tasks may be sufficient to achieve acceptable risk if slightly more reliable pumps and valves are available. It must be remembered, however, that the two pumps and one valve in the analysis are only three equipment units in a system with at least eight other units that each have the capacity to cause total failure of the system. Also, the system is only one of several systems that each have the capacity for causing a complete loss of propulsion, such as the fuel oil or lubrication oil system.

OREDA is the most comprehensive resource available for the reliability of offshore systems and is assessed to also be the most applicable database available for marine systems as explained in Section 2.3, but there are important limitaitons to be considered. Only data on hardware failures is collected in the database. Human error might have been the undelying cause of some hardware failures included in the database. Also, human intervention might have prevented failures not included in the database, as well. The failure rate in OREDA is assumed to be constant over the lifetime of equipment units. Even though random failures dominate the failure distribution of many equipment units [28], this is a simplification. For the main part of the failure events in the OREDA database the beginning and end life of equipment units, which typically have a higher than average probaility of failures, is not included. Failures which happen outside the boundary of the equipment unit specified in the OREDA handbook, but which still affects the output of the unit, is not included. This could be failures to drive or control units. The failure rate estimates presented in the OREDA handbook must be considered to be a minimum over the entire life cycle of the equipment unit [27] and the risk assessments based on these are likely to be non-conservative.

The limitations of the reliability data from OREDA is acknowledged but the accuracy of results presented in the case study is evaluated to be within acceptable margins. For unmanned operation of cargo ships, however, the case study should not be seen as an analysis of a proposed unmanned system. Rather it should be seen as an indication of the shortcomings of using existing machinery systems, designed for manned operation, on UMS. An unmanned system, based on the findings in this paper, would need more redundancy, more remote operation capabilities, and more actuators and sensors. This, in turn, would create a more complex system with more sources of potential failures. On the other hand, the analysis in the paper is performed using failure rate data from the OREDA database [27] which is collected from existing systems designed for manned operation with all the assumptions that this entails.

Reliability of machinery is always a concern in the design of a system, but it must also be balanced with cost. The OREDA handbook presents data collected from real systems which may not have the highest achievable reliability. It may not have been technically feasible to invest in higher quality equipment to improve reliability or to install advanced condition monitoring equipment to detect potential failures on the assumption that corrective maintenance actions could be taken to reduce the risk to an acceptable level when a failure occurred. On a UMS where the same corrective maintenance actions cannot be performed and where the consequence of a failure might therefore be different, it may be cost effective to invest in advanced condition monitoring systems or equipment with higher inherent reliability.

5.4. Maintenance of unmanned cargo ships in the future

Failure detection does not prevent failures, it only detects failures or potential failures. When used correctly, condition monitoring can minimise collateral damage to equipment, reduce the need for unplanned operation stops and avoid unnecessary maintenance [39], but it does not eliminate the need for maintenance.

Unmanned operation may tip the business case in favour of more condition monitoring. The reason for this, however, is not because condition monitoring would be easier or cheaper on a UMS than on CS, but because the costs of failure may be higher. The introduction of UMS might necessitate increased use of condition monitoring, but it does not enable it – as such. Continuously measured failure indicators, as described in Section 2.2.4, could easily be transmitted to a shore control centre and some operational check may be carried out remotely. Many condition monitoring techniques, however, rely on human presence, handheld equipment and/or partial disassembly of equipment units, such as thermography or electrical resistance testing, not to mention inspections by human sensory inputs. There are no condition monitoring methods that can be used on a UMS which cannot also be used on a CS, but there are many that are used on a CS which cannot be used on a UMS

With advances in maritime data communication and sensor technology, as well as an increasing focus on maintenance as an instrument for operational and performance optimization, the breakeven point for when condition-based and predictive maintenance is cost effective may change in the future.

6. Conclusion

In this study, amendments to the RCM method for assessing reliability challenges and maintenance needs of unmanned ships are proposed. The applicability of the conventional RCM method for use on unmanned cargo ships is examined and the differences and similarities with respect to maintenance between conventionally manned and unmanned cargo ships are analysed. The analysis shows that the RCM method is generally well suited for maintenance management and the investigation of reliability issues for unmanned operation, but there are also limitations. Many corrective maintenance tasks are implicitly included in the operational scenario and the effect of these corrective maintenance tasks is not as visible as the preventive maintenance tasks explicitly resulting from the RCM analysis. A more structured way of assessing the effects of corrective maintenance tasks is therefore proposed in this paper. A method is also proposed for assessing the impact from long unmanned voyages on the development of failures in systems with redundancy before the system can be accessed and repaired.

The amended RCM method is tested on a case study of a real machinery system, i.e., the Main Engine (ME) Low Temperature (LT) Fresh Water (FW) cooling water system. For the case study, no major differences were found in the proposed preventive maintenance tasks between manned and unmanned operation. On manned cargo vessels, preventive maintenance work is currently performed both while the vessel is at sea and in port, but in the unmanned scenario in this paper, all maintenance work must be done in port. This was found to be realistic for the proposed preventive maintenance during port calls, both with regard to the number of work hours required and the maintenance task intervals if the operational pattern of the unmanned cargo ship is similar to that of a typical manned vessel of this type. The analyses in this paper, however, do not indicate whether it will be possible to perform all the needed maintenance while the vessel is in port without interfering with the normal operation of the cargo ship, as the maintenance tasks proposed for the analysed machinery system are only a very small part of the total maintenance work burden.

Major differences in the possibilities for performing corrective maintenance between manned and unmanned operation were found, because corrective maintenance chiefly depends on the ability of the onboard crew to make physical repairs. Without humans present on the unmanned cargo ship at sea, the possibilities for performing corrective maintenance are severely restricted, which has a major impact on the consequences of failures. To achieve an acceptable risk level on unmanned cargo ships, increased redundancy in some form is found to be necessary for all the analysed equipment units.

Design changes that reduce the risk level to an acceptable level are proposed. The risk is found to be manageable with design changes to the unmanned cargo ship for the analysed system but is not found to be lower for unmanned operation than for manned operation in any scenario. The main difference between manned and unmanned operation regarding reliability is found to be the greatly differing possibilities for corrective maintenance actions. This presents a major challenge to the unmanned operation of commercial cargo ships.

CRediT authorship contribution statement

Stig Eriksen: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **Ingrid Bouwer Utne:** Conceptualization, Resources, Writing - review & editing. **Marie Lützen:** Validation, Writing - review & editing, Supervision.

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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Appendix

Fig. A.1 in this appendix shows the details of the risk assessment of the ME LT FW circulating pumps and thermostatic regulation valve which are not displayed in detail in the main text. The details of the results of specific failure modes are explained.

$$\lambda_{Total} = \lambda_{Critical\ failure} \cdot \lambda_{Fail\ to\ start\ on\ demand} \tag{A.1}$$

The failure rate of the Failure Mode "*Critical failure + fail to start on demand*" is calculated as the rate at which any of the critical failure modes of the ME LT circulating pumps will occur and where the stand-by pump subsequently fails to start on demand.

‡When there is redundancy of equipment units, as is the case with the ME LT circulating pumps, the risk level is initially assessed using the probability and consequence of one equipment unit failing and the redundant unit(s) being able to take over the function of the failed unit. In redundant systems, there is also the possibility of failure of all the redundant units within a specified time period, which will typically have severe consequences. For many equipment units, such as the ME lube oil cooler and the thermostatic regulation valves, the probability of multiple units failing within the duration of a typical sea passage of a ship is so insignificant that this possibility can be ignored. For the ME LT FW circulating pumps, however, the probability of experiencing failures of multiple equipment units is a real possibility. This should especially be considered for long unmanned voyages, where there is little possibility of repairing a failed unit at sea.

Eq. (A.2) calculates the reliability of a system with redundancy in the equipment units with k units over the time period t, where one is running at a time while the others are in stand-by, and where λ is the failure rate. The equipment units have identical failure rates and there are no failures in the stand-by mode.

$$R(t) = e^{-\lambda \cdot t} \cdot \sum_{i=0}^{k-1} \frac{(\lambda \cdot t)^i}{i!} \tag{A.2}$$

Time period t is 1 day for UMS Short and for manned operation and 14 days for UMS Long.

Eq. (A.3) calculates the probability of experiencing a failure of multiple units over the course of one year of continuous operation of voyages with duration t.

$$F_t(t) = 1 - R(t)^{\frac{365}{t}} \tag{A.3}$$

For small values of λ, $\lambda \approx F_t$.

The failure rate of the Failure Mode "*Two independent failures*" is calculated as the rate at which both ME LT circulating pumps will experience any of the critical Failure Modes of this equipment unit type over a year of continuous operation of voyages with duration t.

			Scenario 1: Preventive maintenance only			Scenario 2: Preventive and corrective maintenance									Scenario 3: System redesign *Redundancy equipment unit*								
						Manned			UMS Short			UMS Long			Manned			UMS Short			UMS Long		
	Failure Mode		C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R
ME LT circulating pumps	Spurious stop	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	External leakage - process medium	Critical	1	4	M	1	4	M	1	4	M	1	4	M	1	4	M	1	4	M	1	4	M
	External leakage - process medium *	Degraded	4	3	**H**	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	External leakage - utility medium	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	External leakage - utility medium	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Internal leakage	Critical	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L
	Internal leakage	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Plugged/Choked	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Plugged/Choked	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Breakdown	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Structural deficiency	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Structural deficiency	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Low output	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Critical failure + fail to start on demand †		4	2	**H**	3	2	M	4	2	**H**	4	2	**H**	1	2	L	1	2	L	1	2	L
	Two independent failures ‡		4	2	**H**	3	1	M	4	1	M	4	2	**H**	1	1	L	1	1	L	1	2	L
Thermostatic regulation valve	Fail to regulate	Critical	4	1	M	3	1	M	4	1	M	4	1	M	1	1	L	1	1	L	1	1	L
	Fail to regulate	Degraded	2	1	L	2	1	L	2	1	L	2	1	L	1	1	L	1	1	L	1	1	L
	Spurious operation	Critical	4	2	**H**	3	2	M	4	2	**H**	4	2	**H**	1	2	L	1	2	L	1	2	L
	Spurious operation	Degraded	2	1	L	2	1	L	2	1	L	2	1	L	1	1	L	1	1	L	1	1	L
	External leakage - process medium	Critical	4	2	**H**	3	2	M	4	2	**H**	4	2	**H**	1	2	L	1	2	L	1	2	L
	External leakage - process medium	Degraded	4	2	**H**	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L

C = Consequence *L = Low*
P = Probability *M = Medium*
R = Risk *H = High*

Fig. A.1. Risk assessment of ME LT circulating pumps and thermostatic regulation valve

* The ME LT circulating pumps are fitted with an auto-start function which will activate the stand-by pump if the outlet pressure of the operating pump decreases below a predefined setpoint. A critical leakage of process medium from the operating pump, in this case LT cooling water, will activate this function with little or no disruption to the LT cooling water flow. A degraded leakage of process medium may not create a pressure drop large enough to activate the auto-start function. If the degraded leakage remains undetected for long enough, the LT water will drain from the system and cause disruption to the LT cooling water flow, resulting in shutdown of the propulsion.

† The auto-start function of the ME LT circulating pumps relies on the stand-by pump to take over when the operating pump fails. However, sometimes the stand-by pump will fail to start on demand, which may have severe consequences in a system with only two pumps. The OREDA handbook includes information on the rate at which equipment units fail to start on demand. Equation A.1 calculates the rate at which a failure mode is experienced and where the stand-by unit will subsequently fail to start on demand.

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Paper IV*

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**Appended as submitted in content but reformated for readable and uniform presentation*

The impact of redundancy on reliability in machinery systems on unmanned ships

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ABSTRACT

Unmanned and autonomous cargo ships may transform the maritime industry, but there are issues regarding reliability of machinery which must first be solved. This paper examines the effect of voyage length on the reliability of machinery with redundancy on unmanned ships. The limiting effects of dependent failures on the improvement of reliability through the use of redundancy is also explored. A strong relationship between voyage length and probability of independent failures in systems with redundancy is shown. Increased redundancy can easily counteract this negative effect of long unmanned voyages on reliability. Dependent failures, however, are not affected by increased redundancy. The contribution of dependent failures on the total probability of failure is found to easily exceed the contribution from independent failures if even a slight proportion of the failures are dependent. This has serious implications for unmanned ships where the possibility of corrective maintenance is very limited and the consequences of mechanical failures on e.g. the propulsion of the ships can therefore be expected to be more severe than on conventionally manned ships. Redundancy in itself may not be enough to provide the reliability of machinery systems required for unmanned operation and other solutions must therefore be found.

KEY WORDS

Shipping; Autonomy; Unmanned; Reliability; Redundancy

1 INTRODUCTION

Unmanned and autonomous cargo ships are expected by many to revolutionize the maritime industry in the coming decades (Kobylinski 2018). With improved sensor and computing capabilities together with the elimination of the on-board crew, the ships of the future are expected to be safer and more efficient with regard to both operation and energy consumption, see e.g. Rødseth ØJ and Burmeister (2012). Others caution that the expected benefits may not be so easily gained and that removing the crews from the ships will cause other as yet unknown issues (Ahvenjärvi 2016; Eriksen 2020). Failures of machinery is a serious issue on

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modern cargo ships and will be even more critical if the operation is to be unmanned because of the severely restricted possibilities for performing corrective maintenance when the ship is at sea. If the requirement is that unmanned ships (UMS) of the future must be as safe or safer than the conventionally manned ships (CMS) of today as suggested by e.g. Kretschmann et al. (2015) and de Vos et al. (2020), there are problems regarding reliability and failures of machinery which must be resolved. This paper will examine issues regarding reliability of machinery systems where redundant components are used in relation to unmanned operation of cargo ships.

There is great variability in the size, construction, operation and voyage lengths of modern cargo ships. Some are never at sea for more than a few hours while others, such as the many ships in the transatlantic or transpacific trade, can be underway for two weeks or more (Lloyd 2014). Cargo ships are self-contained units which rely on their own systems for power, propulsion, communication, etc. CMS rely heavily on their crew for corrective maintenance and failure mitigation at sea (Eriksen et al. 2021). Because of the absence of a crew on a UMS, corrective maintenance cannot be relied on to the same degree. If a ship experiences a loss of steering or propulsion at sea which cannot be rectified it could result in collisions, groundings, and disastrous environmental damages. It would be possible to transport people to the ship during unmanned sea voyages or to salvage it by external assistance but only at great expense and considerable risk. A UMS is therefore practically isolated from physical intervention at sea. This operational scenario of being inaccessible for very long periods and not being able to safely power down without severe consequences sets UMS apart from other forms of transport such as airplanes, trucks and trains as well as industrial processes such as electrical powerplants and manufacturing facilities.

Even though their basic function is still to transport cargo on water, modern cargo ships are as different from their predecessors of a century ago as a wheelbarrow is from a modern highway truck. Today's commercial cargo vessels are marvels of automation and can transport more cargo, with better fuel efficiency, fewer accidents, and with fewer crewmembers onboard than ever before. These developments have been achieved through a continued organic evolution driven by the pursuit for efficiency. Shipping is a fiercely competitive business and developments which do not benefit the profitability will typically not survive unless they are mandated by regulation. Modern ships are very advanced, but they are also 'work-horses' which are built in an open competitive market where cost and build time are important factors. Significant work goes into the design of each ship, but most cargo ships are very much run-of-the-mill constructions and the ships' machinery systems are typically standard off-the-shelf units. Most ships are not on the cutting edge of the technological development and they are not afforded the same resources for research, development and testing as e.g. state-of-the-art naval vessels. At the same time, ship designs are not standardised in the same way as aircrafts, trucks and cars. The design of ships and their machinery systems are often unique and most commercial cargo ships are effectively sailing prototypes.

Ships are not constructed as one unitary vehicle in the same way as a car, truck or airplane but are rather as a combination of individual equipment units or equipment systems originating from several different suppliers (Merenluoto 2018). The ship operator typically deals directly with the individual equipment manufacturers instead of the ship builder regarding maintenance issues, failures, etc. At the same time the machinery systems are also highly interconnected. The main engine is a prime example of this complexity. Unlike small boat engines, large propulsion engines on commercial ships are not self-contained units but require external systems for cooling, fuel cleaning and conditioning, lubrication, etc. A failure in the function of any of these supporting systems will result in the loss of propulsion which is a potentially disastrous situation. However, many of the equipment units which make up the ship machinery systems so vital for propulsion are not very reliable (Downer 2009; Tarelko 2018).

Redundancy can improve the reliability of systems by orders of magnitude compared to single component operation. There are, however, limitations to the level of reliability that can be achieved through redundancy in real applications (Downer 2009). Unintended or unforeseen connections or dependencies between redundant components can invalidate the effects of redundancy on reliability. Extensive theoretical work has been done on this issue. Ebeling (2004) gives an introduction to reliability and maintainability in which the basic mathematics of redundancy is explained. Jones (2012) explores the nature and implications of failures with common courses in systems with redundancy. Downer (2009) investigates the limitations of the effect of redundancy on reliability. The negative effects on reliability caused by the increased complexity as a result of increased redundancy are examined by Perrow (1999).

Reliability of machinery is often mentioned as one of the most significant obstacles to unmanned operation of ships and some work has been done on this subject. Rødseth ØJ and Burmeister (2015) conclude that a high level of redundancy, perhaps even complete redundancy of all components, in the machinery systems is required on UMS. Abdelmoula et al. (2017) evaluates an existing seawater cooling system and conclude that added redundancy is needed if the system is to be used on a UMS. Eriksen et al. (2021) propose an amended Reliability Centered Maintenance method for the use on UMS. The method is used in a case study on a low temperature cooling water system, and it is concluded that more redundancy of machinery and/or more reliable equipment units will be needed. Abaei et al. (2021) present an approach for predicting failure rates of unattended machinery plants given multiple failure modes with random failure distributions. Brocken (2016) analyse a proposed machinery system on a UMS and proposes increased redundancy as a method to obtain an acceptable level of risk. Other authors agree that reliability of machinery equipment will be an issue on UMS and that increased redundancy will be needed, see e.g. Rødseth and Mo (2014) and (2016), Jacobsen (2016), Jokioinen et al. (2016), Jalonen et al. (2017), and Hogg and Ghosh (2016).

Most work done on the machinery systems of UMS suggests that reliability of machinery will be a serious obstacle towards their implementation and that more redundancy will be required for their safe operation. The limited effect of redundancy on reliability and the negative effects of redundancy on the complexity of systems is well understood but this knowledge has so far not been included in the examination of reliability and redundancy on UMS. If unmanned operation of large commercial cargo ships is to become reality the extent to which redundancy can provide the required reliability in its machinery or if other solutions are needed must be understood. Hence, the objective of this paper is to address and explore this issue by examining: (i) the influence of long unmanned voyages on the reliability of ship systems; and (ii) the limitations of redundancy in the improvement of reliability of ship systems and the implications of these limitations on the operation of UMS.

2 IMPORTANT CONCEPTS AND METHODOLOGY

This section describes the operational scenario under which the UMS is assumed to operate. The concepts of failure, reliability and redundancy are also described, and the methodology used in the analysis is explained.

The focus of this paper is on the probability and consequences of failure in machinery systems on large, unmanned cargo ships capable of long intercontinental voyages. No such ship is in operation today, but several standardised definitions of these proposed unmanned and/or autonomous ships exist, see e.g. IMO (2019), Lloyd's Register (2016); Rødseth ØJ and Nordahl (2017). However, none of these definitions are yet recognised within the industry. Also, common to all the definitions is that they mostly focus on the navigational abilities of the vessels. As a result, none of the standardised definitions are found to be sufficiently detailed for the purpose of this paper because of its focus on the ships' machinery systems. Therefore, the analysed operational scenario is described as follows. The ship is unmanned during sea passages. In port and during port arrivals or departures, the ship is manned or accessible to people for repairs. Crews can only enter the ship for maintenance and failure mitigation when it is in port or close to port. Redundant equipment can be put into service during sea passages in case of a failure, but the failed unit cannot be brought back to an operational state until the end of the voyage. Different ships have different operational patterns, but in this operational scenario, it is assumed that the ship is at sea for half the total operation time.

2.1 Failure and failure rate

A failure is defined by CEN (2010) as the 'termination of the ability of an item to perform a required function'.

The distribution of failures over time can be described by the three failure characteristics (ABS 2018):

- Wear-in failure – Highest probability of failure at beginning of component life and decreasing with age.
- Random failure – Constant probability of failure over component life, meaning that the age of the component has no impact on the rate of failure.
- Wear-out failure – Lowest probability of failure at beginning of component life and increasing with age.

The failure rate distribution of most components is a combination of the three failure characteristics. It was previously believed, and according to Moubray (1997) it is still often wrongly assumed, that identical items performing under similar conditions will perform consistently for a period and wear out and fail at roughly the same time. However, the failure distribution for many components, especially complex units, is in fact dominated by random failures which account for between 77 and 92 per cent of failures (NASA 2008).

2.2 Failure rate data

Failure rate data is typically collected through testing or through reporting from operational systems. Despite the long history of commercial shipping, no comprehensive and publicly accessible database of reliability exists for ship machinery systems. For the examples in this paper, reliability data from the Offshore Reliability Database (OREDA) is used instead (SINTEF 2002). The OREDA handbook is the most comprehensive resource of reliability data in the maritime domain (Borges 2015). There are important differences between offshore installations and ships, but many of the equipment units used in their machinery systems are identical or very similar. The operating conditions of machinery systems are also assessed to be sufficiently similar on ships and offshore structures. The OREDA database has been used in several other studies relating to ships, see e.g. Handani et al. (2011), Seo et al. (2013) and Michala et al. (2016).

2.3 Reliability

Reliability is the probability of non-failure over time (Ebeling 2004). Data on reliability does not provide an answer as to when a unit will fail, only the probability of the unit failing within a period of time. On average, reliable units will run for longer before failure but some very reliable units may fail almost immediately, and some unreliable units may run without failure for a long time. Common to all units, however, is that the longer the period of time chosen for consideration, the higher the probability of failure will be.

2.4 Redundancy

Redundancy in machinery systems means that if one element fails, one or more redundant element(s) are in place and can take over the function of the failed element (Downer 2009). Redundancy can be active, or it can be passive, also called standby redundancy. In a system with active redundancy all units operate at the same time but if one fails, the others can perform the function on its own. In a standby redundant system, only one unit is operating at a time. If the operating unit fails, the other will be put into operation and take over the function.

Failures can be either independent or dependent (Rausand and Haugen 2020). An independent failure of one unit will not have any influence on the probability of failure of another unit and there is no common cause linking the two failures. Dependent failures can be either common cause failures or cascading failures. A famous example of a cascading failure is the Apollo 13 accident where the explosion and rupture of one oxygen tank damaged a valve for the other redundant oxygen tank, causing the complete loss of oxygen (NASA 1970). Common cause failures occur when otherwise separate equipment units fail because they are subjected to the same external effects. A salient example of a common cause failure is the loss of propulsion and near grounding of the cruise ship '*Viking Sky*' where three seemingly isolated diesel generators all experienced a loss of lubrication oil pressure caused by a combination of improper operational practises and adverse weather conditions which resulted in an electrical blackout (AIBN 2019).

2.5 Methodology

This section presents the equations used in the present paper. The methods shown here are equations used in the field of reliability and maintainability engineering. Ebeling (2004) is used as the source in this paper, but the equations are generic and can be found in many other textbooks on the subject.

Equation 1 (Ebeling 2004) expresses the probability of failure of a single unit with failure rate λ in failures per unit time over period t when the failure distribution is random as will be assumed in the present analysis.

$$F(t) = 1 - exp(-\lambda \cdot t) \tag{1}$$

Equation 2 (Ebeling 2004) is used to calculate the Mean Time To Failure (MTTF) for random failure distributions. For small values of λ, $\lambda \approx F(t)$.

$$MTTF = 1/\lambda \tag{2}$$

Equation 3 (Ebeling 2004) is used to calculate the probability of either of two failures occurring. The failures are not mutually exclusive.

$$F_{total}(t) = F_A(t) + F_B(t) \tag{3}$$

Equation 4 (Ebeling 2004) expresses probability of failure of a configuration with redundancy over a longer period of y years in which multiple voyages of duration t days are undertaken. The configuration has k equipment units where one is running at a time while the others are in stand-by. The units have identical random failure rates and there are no failures in the stand-by mode.

$$F_r(t; y) = 1 - \left(exp(-\lambda \cdot t) \cdot \sum_{i=0}^{k-1} \frac{(\lambda \cdot t)^i}{i!} \right)^{\frac{365 \cdot y}{t}} \tag{4}$$

3 RESULTS AND ANALYSIS

In this section, the effects of independent and dependent failures on reliability are illustrated through a case study. First, the reliability for units without redundancy is explored. The effect of redundancy is then examined under which the effects of independent failures and dependent failures are examined separately. The scenario for the case study is a UMS with one engine as the only means of propulsion. The consequences of a loss of propulsion will therefore be a serious failure as described in section 1. Two voyages of different lengths are analysed to show the effect of voyage length on reliability. Fourteen days is chosen as an example of a long voyage and one day is chosen as an example of a short voyage.

Pumps are chosen as the equipment unit for analysis in this example because they are one of the less reliable types of equipment unit and are often configured with standby redundancy. Pumps are in the present paper used as an example of one of many types of equipment units which are essential for the operation of machinery systems on CMS today and which will also be needed on the UMS of tomorrow. Pumps are used in many auxiliary systems necessary for operation of the main engine such as cooling water systems, fuel oil systems and lubrication oil systems. If both/all pumps in the standby configuration fail, the system in which it is operating cannot deliver its output, which will result in the failure of the propulsion of the vessel.

Data from the OREDA handbook is used as the basis of the reliability calculations (SINTEF 2002). Only critical failures are considered and the failure rate for the aggregated category containing all types of pumps is used. There are a total of 524 failures recorded in this category over a total of $8.67 \cdot 10^6$ hours in operation. The failure rate λ is therefore $524/(8.67 \cdot 10^6)$ failures/hour. Similar to OREDA, the failure rate is assumed to be constant.

3.1 UNIT WITH NO REDUNDANCY

As explained in section 2.3, time is always a factor in reliability. The longer the period that is considered, the more time the unit will have to fail and the lower the reliability will be. For a single unit operating without redundancy and for relatively small values of λ, typical of real failure rates, and for realistic voyage lengths of less than approximately 50 days, the relationship between voyage length and the probability of failure is found to be almost linear when using equation 1. Therefore, the probability of experiencing a failure in a single unit on a fourteen-day voyage will be almost fourteen times higher than on a one-day voyage. When the same time period is considered, however, the length of the individual voyages does not matter. The probability of failure on one fourteen-day voyage compared to fourteen individual one-day voyages is identical. For a pump operating without redundancy over one year where the ship is in operation for half of the time, the probability of failure is 23% (eq.1). A probability of failure of almost 1 in 4 is very high and would be considered unacceptable for most applications for which the consequence of failure is significant. The Mean Time to Failure (MTTF) for the same scenario is only 3.8 years (eq. 2).

3.2 Redundant units

3.2.1 Independent failures

Redundancy will generally significantly reduce the probability of failure of the system as a whole. If a standby redundant configuration of two pumps is used instead of one pump in isolation, the probability of independent failures over one year of operation, where the ship is in operation half the time, is calculated using Equation 4. For multiple one-day voyages over one year, the probability of independent failures is 0.02%. For multiple voyages of 14 days, the probability of independent failures is 0.26%. When only independent failures are considered, the reliability for one-day voyages has been improved by a factor of over one thousand through the use of redundancy, and for the fourteen-day voyage, it has been improved by almost one hundred.

For small values, the failure rate λ is very close to the probability of failure F_r and the latter can be used instead of the failure rate in Equation 2. For one-day voyages, the MTTF is approximately 5,200 years. For fourteen-day voyages, the MTTF is almost 380 years.

It is clear that redundancy can greatly reduce the probability of independent failures. What is also evident is that when redundancy is used, unlike for single unit systems, the reliability becomes dependent on the length of the individual voyages within a longer fixed period.

If three pumps are used instead of two, so that one is running and two are standby redundant, the probability of independent failures during one year of fourteen-day voyages can be reduced to 0.0018%.

3.2.2 Dependent failures

Besides the probability of experiencing independent failures, there is also a different and separate probability of experiencing a dependent failure. Failure rate data such as that from the OREDA database (SINTEF 2002) is always difficult to determine, but for dependent failures it is even harder because the probability of failure for otherwise identical equipment units changes for each individual application. Because dependent failures are often very rare events, they also cannot be practically tested in a laboratory setting. Designers and manufacturers go to great lengths to predict and avoid causes of dependent failures using methods such as Failure Mode and Effect Analysis (FMEA) (Downer 2009). These methods are sophisticated, but according to Downer (2009), they rely heavily on engineering knowledge and using them requires more art than science. To minimise the sources of common causes of failures, equipment units are often placed in different locations and perhaps even in totally separated engine rooms. Achieving true independence of equipment units, however, is extremely difficult. Examples such as the almost disastrous incident of the '*Viking Sky*' (AIBN 2019), as well as numerous failures in the position keeping of Dynamic Positioning vessels (Vinnem 2003), have shown that redundant and seemingly independent equipment units will often be connected in unforeseen ways or be exposed and fail as a consequence of unexpected external influences.

OREDA does not distinguish between independent and dependent failures nor has any other source of failure rate data for dependent failures been found. Jones (2012) proposes that as much as 10% of failures are dependent failures, although it is unclear how this number is reached. To investigate how even small numbers of dependent failures will affect reliability, it is assumed that 1% of the failures for the pumps used in this case are dependent. As dependent failures affect all redundant units simultaneously, the probability of failure can be calculated as a failure of a single unit using Equation 1. In the present case the probability of dependent failures over one year in isolation is then $2.6 \cdot 10^{-3}$. Compared to the probabilities of failure for independent units, this is a large number. By coincidence, it is almost exactly as large as for independent failures for the two-pump configuration on fourteen-day voyages. Compared to the one-day voyages, it is about 14 times larger.

The total combined probability of independent and dependent failures can be calculated using Equation 3. The 1% of failures which are dependent are subtracted from the total failure rate so that the remaining 99% are independent. For the two-pump configuration over one year, the total probability of failure is $2.8 \cdot 10^{-3}$ for the one-day voyage and $5.3 \cdot 10^{-3}$ for the fourteen-day voyages. For fourteen-day voyages, the contribution of dependent and independent failures to the probability of failure is roughly 50-50. For one-day voyages, however, the contribution of independent failures only increases the total probability of failure by 7.7%. When the three-pump configuration is considered, the contribution of independent failures almost disappears and the total failure rate stabilises at $2.6 \cdot 10^{-3}$ for both one-day and fourteen-day voyages, which is equal to the dependent failure rate. It is evident that redundancy cannot reduce the failure rate of a system to less than that of the dependent failure rate, as Jones (2012) also explains. The MTTF in this example cannot be higher than about 380 years, and the probability of failure over 30 years cannot be better than 2.6%.

3.3 Summary of results

A summary of the results is seen in Table 1. It is clear that the use of redundancy can make systems made up of otherwise fairly unreliable equipment units significantly more reliable. Using two pumps instead of one can reduce the probability of failure by a factor of almost one hundred in the case of one-day voyages. When independent failures are considered in isolation, extremely low probabilities of failures and very high MTTF can be achieved through redundancy. When even a slight possibility of dependent failures is considered, however, this extreme reliability is no longer achievable.

Voyage length has a great impact on the probability of independent failures, but this impact is strongly diminished by the influence of dependent failure. In the two-pump scenario, the voyage length still has an influence on the reliability when dependent failures are considered. For the three-pump configuration, however, the contribution of the independent failures on the total probability is inconsequential.

When only independent failures are considered, added redundancy can improve the reliability by many orders of magnitude. However, these dramatic improvements cannot be realised when dependent failures are also considered. In this example, the improvement from a two-pump to a three-pump configuration is reduced to 50% for the fourteen-day voyages and only 7.7% for the one-day voyages.

Table 1 Summary of reliability and MTTF results

		Dependent failures	One pump	Two pumps		Three pumps	
				One-day	Fourteen-day	One-day	Fourteen-day
Independent failures only	Prob. of failure 1 year	$\sim$	0.23	$0.19 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$	$0.009 \cdot 10^{-6}$	$17.9 \cdot 10^{-6}$
	MTTF [years]	$\sim$	3.8	≈ 5200	≈ 380	$\approx 10\ mio$	≈ 5500
	Prob. of failure 30 years [%]	$\sim$	99.96%	0.5%	7.6%	0.0003%	$0,05\%$
Independent and dependent failures	Prob. of failure 1 year	$2.63 \cdot 10^{-3}$	$\sim$	$2.8 \cdot 10^{-3}$	$5.3 \cdot 10^{-3}$	$2.63 \cdot 10^{-3}$	$2.63 \cdot 10^{-3}$
	MTTF [years]	≈ 380	$\sim$	≈ 350	≈ 190	≈ 380	≈ 380
	Prob. of failure 30 years [%]	7.63%	$\sim$	8.8%	15.3%	7.63%	7.68%

4 DISCUSSION

The effects of long voyages on the probability of failure will be different on a UMS than on a CMS because of the restricted possibilities for performing corrective maintenance when the ship is at sea. On a CMS, it would in many cases be possible to bring the failed unit back to an operational state during the sea passage, but on a UMS this would be almost impossible and the unit will remain in a failed state until the ship can be accessed again in the next port. As a result, the probability of independent failures on UMS will increase almost proportionally with increasing voyage length. This issue is easily solvable with increased redundancy. Dependent failures, however, are not solved through increased redundancy. When even a slight possibility of dependent failures is considered, the contribution of this to the total probability of failure easily surpasses the contribution of independent failures. Unlike independent failures, the probability of dependent failures is not directly affected by unmanned operation and voyage length. There may be issues regarding slowly developing dependent failures which may be harder to detect and almost certainly more difficult to rectify on a UMS than on a CMS at sea, but unmanned operation will not affect the probability of the failures occurring. However, the probability of failure and the factors which influence this are not really significant on their own. To determine the level of risk, the consequences of a failure must also be described (ABS 2018).

Determining risk as the product of probability and consequence by e.g. the use of a risk matrix such as that proposed by ABS (2018) looks deceptively unequivocal, but it must be considered that many different kinds of consequences can be described. Some claim that the consequences of marine accidents in general will be less severe on UMS than on CMS (de Vos et al. 2020). When considering the consequences for human life in isolation, this may, at least initially, be true because of the absence of people onboard. The UMS, however, would still need to be salvaged, which is a dangerous task that has resulted in the tragic loss of several lives (Marine Injury Center 2020). Others point out that the consequences relating to material, economic and environmental damage of marine accidents may be higher because the absence of people onboard makes accident mitigation more difficult (Wróbel et al. 2017). Some argue that the probability of navigation related marine accidents, such as collisions and groundings, will decrease on UMS due to the effect of unmanned operation on human errors (Wróbel et al. 2017). Yet again, other proposes that more near misses related to fire and flooding may develop into marine accidents due to the restricted ability for human intervention on UMS (Eriksen 2020). If the perspective is brought further back, mechanical failures such as described in this paper are likely to have more severe consequences on the propulsion of the ship due to the severely restricted possibility of performing corrective maintenance at sea during unmanned operation (Eriksen et al. 2021).

Despite the effect of long voyages on independent failures and the effect of dependent failures in redundant systems, failures are still quite rare. There is no objective standard for when risk is acceptable and one failure every 190 to 380 years on average may be tolerable. It must be remembered, however, that the examples in the case study in this paper only describe the probability of failure for the pumps operating in one subsystem needed for propulsion. There are several other components in this subsystem, such as heat exchangers, regulation valves, etc., which each have their own probability of failure. The propulsion relies on several of these subsystems and the cumulative probability for loss of propulsion must be expected to be much higher than the ones calculated in the examples. The only reason why such poor reliability can be accepted is because failures can be mitigated or systems can be quickly brought back to an operational state, thereby reducing the consequences and subsequently the risk. On a UMS, these possibilities are drastically limited. This issue has been recognised by several authors such as Abdelmoula et al. (2017), Rødseth ØJ and Tjora (2014) and Eriksen et al. (2021), who propose that increased redundancy is needed for unmanned operation. As this paper shows, however, redundancy may not be enough because dependent failures effectively limit the effectiveness of redundancy on reliability.

Redundancy also carries with it its own problems. More equipment will mean higher costs both for procurement and maintenance, which is an important issue in a competitive business such as shipping. With more redundant equipment as well as more remote or automated controls and actuators needed for UMS, the complexity of the machinery systems increases. This is a particularly troubling issue for UMS, as complexity is often described as the antithesis of reliability (Jones 2012). When systems become more complex, the interrelations between functions and equipment units increases exponentially. The systems become much harder to understand and it will be more difficult to predict the interactions between components. This will increase the probability of dependent failures. Some argue that the complexity resulting from increased redundancy can itself become the primary source of unreliability (Jones 2012).

There are uncertainties in the case study which must be considered. The failure rate data from the OREDA handbook is gathered from real working machinery systems and is thus consists of *realistic* non-idealised values. There are, however, factors affecting the accuracy of the data. Human error might have been the underlying cause of some hardware failures included in the database or human intervention might have prevented other failures. This is not included, as only data on hardware failures is collected in the database. The beginning and end life of equipment units which are subject to wear-in and wear-out failures are typically not included in the OREDA data. Failures of drives or control units, which are outside the boundary of the equipment unit but will nonetheless affect the operation of the unit, are not included in the failure rate data used in the present analysis. The failure rate from OREDA must therefore be considered to be a minimum over the lifetime of the unit (SINTEF 2002). The failure rate is assumed to be constant, and therefore random, over the lifetime of the equipment unit. Random failures will dominate the failure distribution for most components (NASA 2008), but this is still a simplification. Calculating failures as purely probabilistic is of course also an approximation in itself. The probabilistic approach is used in the present analysis to examine fundamental effects of unmanned operation on reliability using generic pump configurations in an 'all-else-being-equal' scenario. Using probabilistic calculations in isolation is a suitable approach for this specific application but the analysis of a real machinery system would require a more comprehensive examination. Methods such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Reliability Centered Maintenance (RCM), and FMEA used in reliability engineering may contain probabilistic calculations but they will also include details of the specific physical installation, operational parameters, and interactions with other units and systems which could affect the probability and consequences of failure. The more accurate information which can be included in the analysis, the better failures can be predicted (Ebeling 2004). The uncertainties presented here are recognized but the results are evaluated to be of sufficient accuracy for the conceptual analysis presented in this paper.

Values on reliability calculated based on OREDA data must be considered to be optimistic. On the other hand, failure rates from OREDA should not be considered as being fixed or the highest achievable. Reliability is always a factor when designing ship or offshore machinery systems, but it must also be balanced with costs. It is possible that more reliable equipment units could be acquired if needed. Online condition monitoring and predictive maintenance is often mentioned as a method to avoid or reduce unexpected failures (Rødseth H and Mo 2014; Brocken 2016). Condition monitoring is already used extensively on CMS today, and it is likely that further developments in sensor technology, advanced failure detection algorithms and maritime data communication will advance its use in the future. For condition monitoring and predictive maintenance be to effective, however, there must be one or more measurable failure indicators, but these do not exist for all failures (Moubray 1997). There must also be enough time from the detection of the potential failure to the occurrence of the actual failure to intervene. This is a particular issue on UMS, where the machinery system cannot be accessed for long periods at a time. Unmanned operation may benefit from or even require increased use of predictive maintenance but does not enable it in any way. On the contrary, there are many condition monitoring techniques which require human presence, handheld equipment and or partial disassembly of equipment units. There are no condition monitoring methods which can be used on a UMS which cannot also be used on a CMS, but there are many that are used on a CMS which cannot be used on a UMS (Eriksen et al. 2021).

The proportion of random failures of 77% to 92% according to NASA (2008) may change in the future. As condition monitoring and predictive maintenance techniques become more advanced, it may become possible to predict the occurrence of a larger part of these failures. On the other hand, the tendency of systems to become more complex is conducive to more random failures (NASA 2008). Except when a specific failure can be reliably detected in ample time before it happens, the occurrence of failures will be probabilistic. An engine, for example, can in most cases run for 500 hours without experiencing a serious failure as assumed in the MUNIN project (Schmidt et al. 2015) but because failure is probabilistic it is always a game of chance. It may be possible to improve the odds of the game and the odds may naturally change over time depending on the failure characteristics, but the game starts over at each time increment that passes.

5 CONCLUSION

In this study, the reliability of machinery in systems with redundancy is explored in relation to unmanned operation of commercial cargo ships. Case studies with different levels of redundancy are examined and it is found, as expected, that the use of redundancy can greatly improve the reliability of a system. In the case studies, the reliability of a redundant system is improved by a factor of approximately one hundred compared to a single unit configuration. When a redundant configuration is used, the case studies finds that the probability of independent failures increases with the length of sea voyages when the failed unit(s) cannot be brought back to an operational state before the next port. Conventionally manned ships rely heavily on their crews for corrective maintenance, and most failures would be possible to rectify during sea voyages. The possibility of corrective maintenance on unmanned ships at sea is severely restricted and if units fail during the voyage, they must likely remain in a failed state until the ship can be accessed by repair personnel at the next port.

Increased redundancy can solve the problem of independent failures. The total probability of failure, however, is the result of both independent and dependent failures and the latter cannot be improved by increased redundancy. When even a small fraction of the failures are dependent the probability of failures resulting from these very quickly surpasses that of independent failures. The probability of failure can never be better than the probability of either dependent or independent failures and the redundancy can therefore only reduce the probability of failure to the probability of dependent failures. Adding more redundancy after this point thereby only serve to increase the complexity and may effectively decrease the reliability.

If the risk of failures in machinery on unmanned ships is not to be greater than on conventionally manned ships, machinery systems must either be made so reliable that the probability of failure in itself makes the risk acceptably low, or it must be ensured that the consequences can be reduced to an acceptable level. Redundancy can greatly improve reliability but because of dependent failures, there is an upper limit to the extent of this improvement. The possibility of corrective maintenance by the onboard crew is instrumental to the mitigation of consequences. Without this important barrier present on unmanned ships, other solutions besides redundancy are likely to be needed.

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Paper V*

Eriksen, S.; Lützen, M. **The impact of unmanned operation of ships on the maintenance workload and related costs, (***Submitted 16 August 2021) WMU Journal of Maritime Affairs*

**Appended as submitted in content but reformated for readable and uniform presentation*

The impact of unmanned operation of ships on the maintenance workload and related costs

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ABSTRACT

Autonomous and/or unmanned ships are projected to revolutionize the maritime transport industry. Unmanned operation, however, does not eliminate the workload required to operate a ship. Some jobs may be automated, and some may disappear from the ship, but many jobs such as maintenance must still be done. Some argue that unmanned ships will be mechanically simpler since the accommodation of a crew is not needed while other argue that more redundancy in machinery will be required. This paper examines whether the workload required to maintain modern cargo ships can be expected to decrease or increase if the ships were to operate unmanned. The study finds that the maintenance workload can be reduced by up to 18 per cent if systems for accommodating the crew can be eliminated. The study also finds, however, that the potential saving is greatly reduced, or that unmanned operation may even result in an increase in the maintenance workload, when the redundant equipment is factored in. The reductions or increases in the maintenance workload are found to be in the one-digit range in all analysed scenarios. This suggests that unmanned operation of commercial cargo ships will not have a significant impact on the maintenance workload and the costs related to this.

KEY WORDS

Maintenance; Autonomous ships; Unmanned ships; Maintenance workload

1 INTRODUCTION

If the operation of commercial cargo ships can be made unmanned and/or autonomous in the future as has been suggested it would have the potential to revolutionize the maritime transport industry. The expected benefits for the unmanned ships (UMS) compared to conventionally manned ships (CMS) include increased cargo capacity due to the elimination of the accommodation, improved safety due to a reduction in human errors as well as reduced fuel consumption arising from less wind resistance and reduced need for electrical power (Kobylinski 2018). Another often mentioned expected benefit is reduced operational costs (Eriksen 2019), of which crew salaries constitute a major part.

Advanced automation and integration of systems and sensors is expected to be able to take over many of the tasks related to navigating and operating CMS today. Removing the crew from the ship does not of

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course mean that the work required to operate the ship and the cost related to this will disappear. Much of the administrative work will likely remain unchanged but can be done ashore and some operational tasks that cannot be automated may be possible to carry out via remote control. Some tasks, however, such as most maintenance jobs, must be done physically on the ship. A few maintenance jobs, such as functional testing of equipment, may be carried out remotely given the possibility for remote monitoring, but the overwhelming majority of tasks require physical access to the equipment. If the ship can be made to operate unmanned there would be no need for the systems and equipment required to accommodate people onboard, such as e.g. air-conditioning, sewage system and lifesaving appliances. Without the need for such systems on UMS the maintenance needed for their upkeep would of course also disappear. Other jobs, however, may arise from the introduction of unmanned operation. UMS will likely require more redundancy of machinery equipment due to the severely reduced capabilities of doing corrective maintenance during sea passages (Rødseth ØJ and Tjora 2014; Abdelmoula et al. 2017; Eriksen et al. 2021). This additional redundant equipment will also require maintenance. This paper will examine whether unmanned operation can be expected to increase or decrease the total workload relating to maintaining the ship.

Some work has been done on maintenance of autonomous and/or unmanned ships. Rødseth H and Mo (2014) propose a maintenance management framework for unmanned ships. The maintenance management framework is further expanded on and implemented in an integrated planning concept for unmanned ships in Rødseth H and Mo (2016). Jacobsen (2016) establishes a procedure for identification of barriers in the maintenance tasks on unmanned cargo ships. Rødseth ØJ and Burmeister (2015) discuss new ship designs for unmanned and autonomous ships and conclude that redundancy of critical machinery systems is necessary to achieve an acceptable level of risk. Other authors agree that increased redundancy will be needed. Brocken (2016) conducts an economic analysis of the proposed machinery systems on unmanned ships. Increased redundancy of machinery is proposed as the answer to obtain an acceptable level of risk and the cost of this is balanced with the elimination of crew accommodation equipment. Abdelmoula et al. (2017) evaluate an existing seawater cooling system of a CMS and conclude that added redundancy is needed if the system is to be used on a UMS. Eriksen et al. (2021) propose a method for maintenance planning for use on UMS and the method is used in a case study on a low temperature cooling water system. It is concluded that more redundancy of machinery and/or more reliable equipment units are needed if the ship is to operate safely unmanned. Several other authors identify maintenance as a challenge on UMS: see for example Jokioinen et al. (2016), Porathe et al. (2013), Jalonen et al. (2017) and Hogg and Ghosh (2016). In addition to increased redundancy it is suggested that more reliable equipment is needed or that ship machinery systems should be simplified to reduce maintenance and minimize sources of failures. It is also proposed that maintenance and maintenance management should be improved and that the use of condition-based and predictive maintenance should be increased.

It is widely acknowledged that maintenance is an important issue in the development of UMS. The question of how unmanned operation will impact the maintenance workload, however, is poorly addressed. Kretschmann Lutz et al. (2017) conduct an economic analysis of an autonomous and unmanned bulk carrier. In the analysis an assessment is made of the required maintenance boarding crew. It is assumed that an engine crew of nine, which is typical for a conventionally manned ship of equivalent size, would be able to carry out all the required maintenance during the time the ships is berthed or waiting at anchor.

The little work that has been carried out is based mainly on assumptions and, so far, no systematic quantitative analysis has been done to assess whether the workload required for maintaining a ship can be expected to increase or decrease with the implementation of unmanned operation. This paper will explore and address this issue through the analysis of maintenance data from five commercial cargo ships. The maintenance of the CMS will be compared to two proposed cases of unmanned operation; one where the ship is always unmanned at sea and one where the ship has the option to periodically accommodate a crew at sea. The study will identify which equipment units or systems will no longer be needed or only needed in a reduced capacity in the two unmanned cases and what effect this will have on the maintenance workload. An assessment of the increase in maintenance workload resulting from the additionally needed redundancy of machinery that unmanned operation necessitates will also be made. These effects will be combined in an evaluation of the total impact of unmanned operation on the maintenance workload of ships.

2 MAINTENANCE OF SHIPS

Maintenance can be defined as "*Ensuring that physical assets continue to do what their users want them to do*" (Moubray 1997) and involves many different tasks from major overhauls of equipment or systems with replacement or reconditioning of parts or subcomponents to more routine tasks such as greasing, cleaning and inspections. The task of maintaining a large commercial cargo ship is vastly different from that of other modes of transportation such as air, road or rail, with which shipping can typically be compared. It is not that the machinery on a ship is very different or more complicated than that of an airplane or a truck. The main difference is that ships are so much larger. Large cargo ships dwarf all other methods of transportation, often by orders of magnitude, in terms of both size and cargo capacity. The largest container ships in the world can each carry the same as more than 12,000 highway trucks (Zhang et al. 2015; MI News Network 2020). In relative terms, cargo ships may be comparatively simple compared to airplanes or trucks but because of the sheer size many more and much bigger propulsion and service systems are needed for their operation. The workload required for the maintenance of these systems is substantial and its magnitude and organization can better be compared to that of electrical powerplants or manufacturing facilities than to that of other modes of transport. Unlike shore-based facilities, however, ships are mobile units which rely on their own machinery for power and other amenities and on the onboard crew for maintenance and emergency response. Maintenance on ships also differs from air, road or rail in that most of the maintenance is done by the onboard crew when the ship is in operation. This is necessitated by the operation where voyages can last weeks and where ships can be far from the possibility of external assistance for long periods. The large size of ships of course also allows for the presence of a permanent maintenance and operations crew, which enables ships to function almost continuously for years without having to be taken out of operation.

Maintenance is essential for the safe, reliable and pollution-free operation of ships (IACMS 2008). In the International Safety Management Code (ISM Code) (IMO) the International Maritime Organization (IMO) dictates that maintenance is to be organized through a Planned Maintenance System (PMS). Classification society regulations may require the PMS to be a computer-based system (DNVGL) and on large cargo ships it typically will be, but the PMS can also be a paper-based system. The PMS is used for maintenance planning and will normally also contain or link to spare part inventories and to relevant maintenance job descriptions. Equally importantly, the PMS is also a record of the history of each contained equipment unit including details of failures, defects and damages, and the corresponding corrective actions. It is not only planned maintenance jobs that are recorded in the PMS, despite its name. Details of unplanned maintenance tasks, or normally planned tasks carried out before their scheduled time due to failure, is valuable information and is also recorded in the PMS. Not all unplanned maintenance is recorded in the PMS, however, nor is this work normally recorded anywhere else. Much of the maintenance of components where scheduled maintenance is not technically feasible, but where failures happen nonetheless, such as pipework, gaskets, and smaller electronic components, is not recorded. Not all planned maintenance tasks are recorded in the PMS either. Some of the more basic or ad hoc tasks for which maintenance schedules are difficult to specify, such as painting or cleaning, are typically not included.

On many ships the Chief Engineer will be overall responsible for the maintenance planning and the engineering department will carry out most of the maintenance onboard. The deck crew is typically also involved in the maintenance, however, and the galley crew or other departments may also be assigned maintenance tasks. The Chief Officer will normally coordinate maintenance on deck where the deck crew will carry out many of the maintenance tasks. The other navigational officers may also have maintenance tasks to carry out or coordinate. The PMS will notify of which maintenance jobs are to be carried in the coming period based on predefined parameters. When the job has been carried out it will be logged in the PMS, along with the time of completion and any relevant measurements taken or other details or comments relating to the job or condition of the unit. If jobs have to be postponed due to operational constraint, for example, this will also be logged.

3 DATA AND METHODOLOGY

3.1 DATA

Three sources of data are used for the analyses in this paper: data on planned maintenance; data on the distribution of the work time of the crew; and data on the operation of ships. The data on planned maintenance and on the operation of the vessels originate from five ships. The data on the work time distribution was collected during fieldwork on one of these five ships. Data has been made available from the Danish shipping company Lauritzen Kosan, which operates a fleet of gas tankers operating in coastal and worldwide trade. The ships vary in size between approximately 4,000 and 10,000 gross register tonnage (GRT) and have a crew of between 13 and 15. The five ships are in either time charter or in tramp trade.

3.1.1 Planned Maintenance data

Data from the five ships' PMS, as described in section 2, have been provided by Lauritzen Kosan for this analysis. All the maintenance data originated from 2019 and 2020. Maintenance data were analysed for a period of five months for four out of the five ships and in the case of the last ship, for a period of one year and four months. The combined time of operation analysed for the five ships therefore totals three years and four months. For the five ships a total of 26,433 maintenance jobs were carried out and recorded in the PMS within this combined time of operation. Many of the maintenance jobs were carried out more than once, such as weekly or monthly checks. There are 3,601 different unique jobs in the data.

The description of each maintenance job contains information such as component name and number, job group name, job name and job number as well as information on interval, when the job was carried out, etc. A job description is often included and remarks on the condition of the component after completion of the job is also often included. Most importantly for the analysis in this paper, the man-hours spent on the maintenance task are also recorded. The volume of analysed maintenance data is significant. If it were to be printed in a standard spreadsheet format it would cover more than 3,000 pages.

3.1.2 Work time distribution data

The distribution of how the work time of the crew is distributed was studied in detail for one of the five ships. Work time distribution data was gathered during a field study onboard the vessel over the course of 10 days in June 2019 during which the ship was in normal operation. The distribution of the work of each crewmember was collected through self-reporting and was captured using a combination of standardized forms and individual interviews. Each of the 15 crewmembers reported several times during the 10-day period on the distribution of their work time both over a longer period and for individual days of work within the period. The data used in this analysis originate from a session in which each crewmember reported on the distribution of their work over a typical month of normal operation in the following categories:

- Shipboard operation (navigation, manoeuvring, cargo operations, bunkering, etc.)
- Maintenance

    - Planned maintenance recorded (PM recorded)
    - Planned maintenance not recorded (PM not recorded)
    - Unplanned maintenance
- Administration (documentation, requisitions of spares and provision, rest hour management, etc.)
- Meetings, inspections, and drills.

The distribution of work time is assumed to be representative for all the five ships in the present case study.

3.1.3 Vessel operation data

Data on the operation of the same five vessels as for which the maintenance data were provided were also made available for the analysis in this paper. The data cover one year of operation on each ship between September 2018 and October 2019. The data was processed, and the operation organised into the following four modes: At sea, At anchor, In port, and Manoeuvring.

3.2 METHODOLOGY

3.2.1 Maintenance job classification

To enable the later analysis of whether a maintenance job would have to be done on a UMS each job is categorized into one of the following categories.

- Crew equipment - *Equipment only relating to the accommodation of the crew*
- Ship equipment - *Equipment relating to the propulsion and operation of the ship*
- Lifesaving appliances - *Life boats, life rafts, pyrotechnics, etc.*
- Manual firefighting equipment - *Fireman's outfits, fire hoses, manual fire extinguishers, etc.*
- Automatic firefighting equipment - *Firefighting equipment that is or can be made to be automatically or remotely activated*
- Tools - *Tools needed for maintenance*
- Navigation and manoeuvring equipment - *Radar screens, operation handles, buttons, etc.*
- Communication equipment - *Radio, satellite, and internal communication equipment*

A detailed description of the categories can be seen in Appendix A. The categories were designed and described in such detail that an evaluator with some engineering knowledge and some familiarity of ship machinery systems but without in-depth knowledge of the particular ships in this analysis would be able to organize the maintenance jobs in the appropriate categories confidently and consistently. On the other hand, the categories were kept so generic that they could easily be used in other analyses on different types or sizes of cargo ships.

The classification of the maintenance jobs was done on the basis of the domain, system and engineering knowledge of the authors. The corresponding author has domain knowledge as a marine chief engineer responsible for operation and maintenance of technical marine systems with 7+ years of experience. A portion of the results was then verified by two students in the in course of Bachelor of Technology and Maritime Engineering who also have practical experience with technical ship systems.

3.2.2 Redundant equipment units

As described in section 1, a UMS would require a larger degree of redundancy of equipment due to the severely restricted possibilities for doing corrective maintenance during sea passages. This increased redundancy of machinery would also require maintenance and thus contribute to increasing the total maintenance workload onboard the UMS. Redundancy can greatly improve the reliability of systems made up of otherwise fairly unreliable components and there is already a high degree of redundancy in many of the auxiliary and service systems onboard CMS (Eriksen et al. 2021).

For the five ships which are the subject of this analysis and for many other cargo ships large equipment units such as main engines (ME), steering gear, and rudder arrangements are not duplicated due to considerations of building cost, maintenance cost, and fuel efficiency. An irreparable failure of the main engine would therefore result in a loss of propulsion; and a failure of the steering gear or rudder arrangement would result in a loss of manoeuvrability. On a CMS the risk of an irreparable loss of the propulsion or manoeuvrability is considered sufficiently low to be acceptable, but only because of a large degree of redundancy in the ME service systems and the ability of the onboard crew to take corrective maintenance actions during operation. On a UMS, however, where the possibility for employing the corrective actions needed to return the machinery to an operable state are severely restricted, the one-engine configuration is likely to be unsafe.

The assumption made in this paper is that the main engine (ME), steering gear, and rudder arrangement is duplicated in its entirety on the UMS. Equipment units that are not part of the physical unit but are nevertheless part of the direct operation of the ME or steering gear, such as oil mist detector or steering gear electronic control system, are assumed to be needed on both redundant units and are thus also duplicated. It is further assumed that the duplication of the ME and steering gear does not affect the interval or duration of the maintenance jobs related to them. Any maintenance jobs done on the singular ME, steering gear, and rudder arrangement on the CMS must therefore be done on both units on the UMS and twice as much total time must consequently be allocated for the maintenance of these units when they are duplicated.

Equipment units that are part of service systems supporting the operation of the ME or steering gear, such as lube oil and cooling water systems, are assumed to be able to service both the main engines or steering gear units on a UMS and would therefore not have to be duplicated in their entirety. These service systems already have a lot of built-in redundancy, although it is likely that further redundancy of individual components within the systems such as pumps or valves would be needed on a UMS (Abdelmoula et al. 2017; Eriksen et al. 2021). However, without an in-depth analysis of each system, which is outside the scope of the present paper, it would not be possible to confidently predict which components would have to be duplicated.

3.2.3 Operational scenarios

In this paper the influence of unmanned operation on the maintenance workload is examined for two cases of unmanned operation of ships. A fully unmanned scenario, case 1, and a periodically unmanned scenario, case 2, is explored. The two scenarios are compared to a base case of the normal manned operation of a CMS. The two unmanned cases follow that of the MUNIN project (Rødseth ØJ and Tjora 2014), which is also similar to that described in the AAWA project (Jokioinen et al. 2016). In both unmanned cases the ship would be able to operate unmanned during sea passages. During normal operation, the onboard control system is able to operate the machinery systems within predefined boundaries independently of human control. One or more shore control centres continuously monitor the UMS remotely and can take over control of the UMS and its systems at any time. A short description of the two cases is given here. A more detailed description can be seen in Appendix B.

In case 1 the ship is always unmanned at sea and is not able to accommodate a crew at any time. All maintenance must therefore be done when the ship is in port. There are no systems for the accommodation of a crew nor are there any lifesaving appliances. Because a repair crew must be able to enter the ship in port and carry out maintenance in a safe manner, there must be some manual firefighting equipment as well as other amenities such as electrical power, compressed air, water, etc. Because of the unmanned operation, increased redundancy as described in section 3.2.2 must be present.

In case 2 the ship is normally unmanned but has the option to accommodate a repair crew when at sea. The systems needed for the accommodation of a crew as well as the lifesaving appliances must therefore be present but in a reduced size and/or capacity compared to a CMS. More manual firefighting equipment than in case 1 but less than in the base case must be present. The other amenities mentioned in case 1 must also be present. Because the UMS must have the option to operate unmanned at sea, the same increased redundancy as in case 1 must be applied.

4 ANALYSIS AND RESULTS

This section presents the results of the analysis based on data presented in section 3.1. The maintenance job categorization and work time distribution is presented in section 4.1. In section 4.2 the analysis of work time distribution data and vessel operations data is presented. The results and analysis of the maintenance data is described in section 4.3. Section 4.3.1 presents the maintenance job distribution of the base case of the CMS. In section 4.3.2 the analysis of the influence of unmanned operation on the maintenance workload is presented and the impact that this have on the overall maintenance workload is described in section 4.3.3. Lastly, in section 4.3.4 the analysis of the total maintenance workload of the UMS is presented.

4.1 MAINTENANCE JOB CATEGORISATION AND WORK TIME DISTRIBUTION

Table 1 shows the maintenance job categories and whether or not increased redundancy is assumed to be included in the three cases. The table also shows the distribution of time spent on maintenance in each job category based on the maintenance data presented in section 3.1. In the base case, the maintenance jobs are taken directly from the maintenance data presented in section 3.1.1. Because the base case is the conventionally manned ship, the increased redundancy that is necessary for unmanned operation is naturally not included. In case 1 and case 2, Table 1 shows which maintenance jobs are assumed to still be carried out as for the base case (+) and which are assumed to disappear with unmanned operation (-). The table also shows which jobs are assumed to be possible to carry out off the ship and for which job categories the maintenance workload is assumed to be reduced. The percentage value signifies the assumed reduction in man-hours for the category compared to the base case.

Table 1 Overview of maintenance jobs in the three cases and distribution of maintenance work time

Job category	**Base case**	**Case 1**	**Case 2**	**Distribution**
Crew equipment	+	-	-50%	6.5%
Ship equipment	+	+	+	74.1%
Lifesaving appliances	+	-	-50%	7.5%
Manual firefighting equipment	+	-50%	-25%	1.6%
Automatic firefighting equipment	+	+	+	5.5%
Tools	+	Off ship	+	3.1%
Navigation and manoeuvring equipment	+	Off ship	Off ship	0.4%
Communication equipment	+	-	-	1.3%
Increased redundancy	-	+	+	N/A

The distribution of work time in Table 1 shows that nearly 3/4 of the maintenance work time is spent on ‘Ship equipment’, which will not be affected by unmanned operation. Only 6.5 per cent of the maintenance work time is spent on systems directly related to the accommodation of the crew. However, an additional 7.5 per cent is spent on ‘Lifesaving appliances’, which is also affected by unmanned operation. The other two categories affected by unmanned operation, ‘Manual firefighting equipment’ and ‘Communication equipment’, only constitute smaller parts of the work time.

4.2 ANALYSIS OF WORK TIME DISTRIBUTION DATA AND VESSEL OPERATIONS DATA

The distribution of work as described in section 3.1.2 is as seen in Figure 1, left. The largest portion of work time is used on "Shipboard operation", which covers such activities as navigation of the ship, cargo operations, cooking, bunkering and the operation of machinery. Almost equal in proportion to shipboard operation is the time spent on maintenance, at 43 per cent of the total work time distributed across the three categories: planned maintenance (PM) recorded at 18 per cent; PM not recorded at 17 per cent; and Unplanned maintenance at 8 per cent. The recorded work time spent on maintenance in the PMS data presented in section 4.3 thus only constitutes a part of the total time spent on maintenance. To determine the total maintenance workload the value for PM recorded obtained from the PMS data must therefore be divided by 18/43.

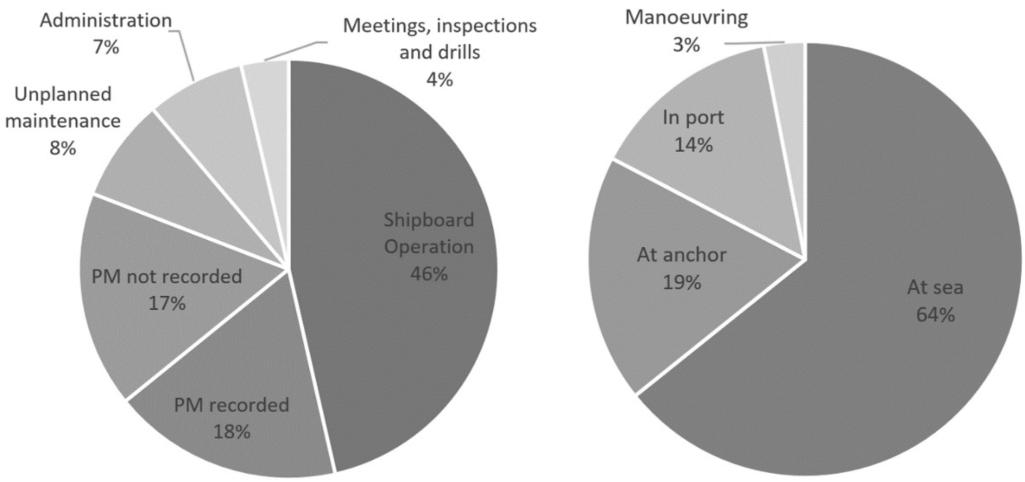

Figure 1 Work time distribution and vessel operation mode distribution

The distribution of time spent in the operations modes of the vessels as described in section 3.1.3 can be seen in Figure 1, right. About two thirds of the total operations time is spent at sea. The vessels are only in port, and therefore available for maintenance in the unmanned case 1, for 14 per cent of the time.

4.3 ANALYSIS OF MAINTENANCE DATA

4.3.1 Maintenance job distribution

The number of work hours spent on maintenance recorded in the PMS data described in section 3.1.1 across all the categories for each of the five vessels is shown in Table 2. PMS data was analysed for different periods for the five vessels as explained in section 3.1.1 but all the values in Table 2 have been normalized to work hours per year per ship. Row one shows the total work hours recorded in the PMS from each of the five ships. As explained in section 2, some unplanned maintenance is also recorded in the PMS data. The time spent on unplanned maintenance recorded in the PMS data for each ship is shown in Table 2, row two. To isolate the work time so as to only include that which belongs in the PM recorded category, as shown in Figure 1, left, the unplanned maintenance in row two is subtracted from the PMS data in row one. The resulting work maintenance work time presented in row three represents the base case in the present analysis.

Table 2 Maintenance work hours per year in the base case

	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5	Avg.
Maintenance work hours per year						
Total work hours in PMS system	8,367	6,468	6,777	4,946	6,558	6,623
Unplanned maintenance in PMS system	1127	212	752	498	577	633
Base case	7,241	6,256	6,025	4,448	5,981	5,990

The proportion of the average values for unplanned maintenance and base case in the PMS data presented in Table 2 is 633/5990 ≈ 11 per cent. In the work time distribution presented in Figure 1, left, the proportion of unmanned maintenance to PM recorded is significantly higher at 44 per cent. There is likely more than one reason for this discrepancy and reporting uncertainty must certainly be considered. The main reason, however, is believed to be that much of the unplanned maintenance is not recorded in the PMS data as also explained in section 2. This proportion of recorded and unrecorded unplanned maintenance is not known. It has therefore been assessed that the most accurate results are achieved by removing the unplanned maintenance from the PMS data, thereby isolating PM recorded for the base case as explained in this section.

4.3.2 The influence of unmanned operation on the maintenance workload

Table 3 shows how much the maintenance workload can be reduced due to unmanned operation, how much additional maintenance work will be needed because of increased redundancy and how much of the maintenance workload can be done ashore.

The reduced maintenance due to unmanned operation presented in Table 3 is calculated based on the assumptions of which maintenance job categories could be eliminated or reduced due to unmanned operation as described in section 3.2.3 and in Appendix B, and as presented in Table 1. For case 1, for example, the ‘Crew equipment’, ‘Lifesaving appliances’ and ‘Communication equipment’ job categories would be eliminated, and the ‘Manual firefighting equipment’ category would be reduced by 50 per cent. As the maintenance workload related to the jobs in these categories does not need to be carried out on a UMS, the workload in case 1, for example, could be reduced by 1,057 hours on average or 18 per cent compared to the base case.

Table 3 Impact of unmanned operation on maintenance workload

		Ship 1	Ship 2	Ship 3	Ship 4	Ship 5	Avg.
Change in workload due to unmanned operation							
Case 1	Hours per year	-1,390	-949	-997	-884	-1,064	**-1,057**
	Per cent of base case	-19%	-15%	-17%	-20%	-18%	**-18%**
Case 2	Hours per year	-771	-503	-555	-495	-574	**-580**
	Per cent of base case	-11%	-8%	-9%	-11%	-10%	**-10%**
Change in workload due to increased redundancy							
	Hours per year	874	837	831	659	916	**824**
	Per cent of base case	12%	13%	14%	15%	15%	**14%**
Change in *onboard* workload due to moving jobs ashore							
Case 1	Hours per year	-313	-243	-190	-170	-228	**-229**
	Per cent of base case	-4.3%	-3.9%	-3.2%	-3.8%	-3.8%	**-3.8%**
Case 2	Hours per year	-26	-47	-22	-18	-19	**-26**
	Per cent of base case	-0.4%	-0.8%	-0.4%	-0.4%	-0.3%	**-0.4%**

As explained in section 3.2.2, more redundancy of machinery would be needed on a UMS and this would contribute to increase the maintenance workload. In section 3.2.2, it is assumed that the ME, steering gear, and rudder arrangement is duplicated. When these specific units are isolated in the PMS data, the work time spent on the jobs relating to them are doubled, as was the assumption, contributing an increase of, on average, 824 hours or 14 per cent compared to the base case.

Besides the possible reduction in maintenance hours due to unmanned operation shown in Table 3, some of the work that must still be carried out can also be moved ashore. The number of hours, and the proportion of this of the base case is also shown in Table 3. Similar to the reduction in maintenance, the values for the work that can be moved ashore is based on the assumptions described in section 3.2.3. The maintenance jobs categories marked in Table 1 as "Off ship" could potentially be done ashore. For case 1 the maintenance workload relating to these categories totals 229 hours per year on average or 3.8 per cent of the base case presented in Table 2.

4.3.3 The impact of unmanned operation on the maintenance workload

The total impact on the maintenance workload presented in Table 4 shows the total impact of both the reduced maintenance due to unmanned operation and the added maintenance resulting from increased redundancy. In case 1 (totally unmanned) the workload can be reduced by 18 per cent as seen in Table 3 and an additional 3.8 per cent can be moved from the ship to shore. When the extra work needed due to increased redundancy, also shown in Table 3, is considered, however, the difference is reduced to only 7.7 per cent. It might be desirable to move some of the maintenance work ashore if possible when the ship is only accessible for maintenance in port. However, the workload and cost related to this work does not disappear. When the overall maintenance workload is considered the reduction in case 1 compared to the base case is only 3.8 per cent.

Table 4 The impact of unmanned operation on the maintenance workload

		Ship 1	Ship 2	Ship 3	Ship 4	Ship 5	Avg.
Impact on the *onboard* workload							
Case 1	Hours per year	-828	-355	-356	-395	-376	**-462**
	Per cent of base case	-11,4%	-5,7%	-5,9%	-8,9%	-6,3%	**-7,7%**
Case 2	Hours per year	77	287	254	146	323	**218**
	Per cent of base case	1,1%	4,6%	4,2%	3,3%	5,4%	**3,6%**
Impact on the overall workload							
Case 1	Hours per year	-515	-111	-166	-225	-148	**-233**
	Per cent of base case	-7,1%	-1,8%	-2,8%	-5,1%	-2,5%	**-3,8%**
Case 2	Hours per year	104	334	276	164	342	**244**
	Per cent of base case	1,4%	5,3%	4,6%	3,7%	5,7%	**4,1%**

In case 2 the possible reduction in maintenance is smaller due to the need for some crew accommodation systems, some lifesaving appliances and more manual firefighting equipment than case 1. The reduction in maintenance is reduced to 10 per cent on average and only 0.4 per cent of the work can be moved ashore. Since the vessel must be capable of unmanned operation it must still have the same level of redundancy as is case 1 which adds 14 per cent to the maintenance workload. As a result, there is an average increase in the onboard workload compared to the base case of 3.6 per cent and an increase in the overall maintenance workload of 4.1 per cent.

4.3.4 Total maintenance workload

The maintenance work hours presented in Table 2 only represent those that are recorded in the PMS. As explained in section 3 and as shown in Figure 1, left, the PM recorded used as the base case in the present analysis is only part of the total maintenance workload. To calculate the total maintenance workload the maintenance work hours as explained in section 4.2, must therefore be divided by 18/43. When using the average value across the five ships for the base case of 5,990 hours presented in Table 2 the total maintenance workload will be 14,311 man-hours. If translated into full-time equivalents (FTE), using the OECD average of 1,726 work-hours per person per year (OECD 2021), the maintenance of the CMS in the base case is the full-time job of 8.3 people. This correlates quite well with the proportions of the work time distribution shown in Figure 1 left. Based on the work time distribution data, maintenance constitutes a total of 43 per cent of the total workload. With a crew of e.g. 14 (see section 3.1) this would mean that maintenance would take up the work of 6 of the crewmembers. Seafarers typically work more hours than the FTE ashore, so the discrepancy is reasonable.

It is assumed that the same relationship of PM recorded to total maintenance workload applies to the reduced maintenance due to unmanned operation, maintenance moved ashore and increased maintenance due to redundancy. The same differences to the workload in case 1 and case 2 presented in Table 4 will therefore also apply to the total maintenance workload. For case 1 for example the total maintenance workload could be reduced by 3.8 per cent from 14,311 man-hours to 13,767 man-hours if the work ashore is included and by 7.7 per cent to 13,209 if it is not. Translated into FTE case 1 could be reduced from 8.3 for the base case to 8.0 if the work ashore is included and 7.6 if it is not. For case 2 the FTE would increase to 8.8. The work ashore for case 2 is negligible in this context.

In case 1 the maintenance work can only be done in port, which constitutes 14 per cent of the total operating time as seen in Figure 1 right. By dividing the total maintenance workload for case 1 excluding the work done ashore by 14 per cent of the hours of a year it shows that it will require the equivalent of 10.8 persons working around the clock at all times when the ship is in port.

5 DISCUSSION

Ships and their machinery systems are designed and constructed to fulfil the functional requirements that the operation of the ship dictates. Reliability and maintainability of machinery are important factors in the design of ships, but these aspects must also be balanced with build and operational costs as well as with energy efficiency. On UMS this balance may shift towards simpler and less maintenance demanding equipment as explained in section 1. This possible shift is not because the cost of purchasing and operating machinery systems is lower on UMS. Nor is reliability any less of an issue on UMS, in fact it is likely to be even more critical (Eriksen et al. 2021). The difference is that the consequence of a failure in these systems would be higher due to the severely restricted possibilities for doing corrective maintenance at sea. If unmanned commercial cargo ships are to become reality in the future, they will almost certainly not be constructed simply as modified versions of the conventionally manned ships of today. With no large unmanned commercial cargo ships in operation today data from CMS must be used in combination with assumptions about the proposed operation of UMS. The description of the operational scenarios and the technical capabilities of the ships and systems as described in section 3.2.3 is based on established scenarios used in other analyses (Rødseth ØJ and Tjora 2014; Jokioinen et al. 2016) but many assumptions have had to be made to supplement these. The assumptions are made with no deliberate bias and the scenarios described are assessed to be of enough detail for the analysis to be valid and balanced, but there are uncertainties that must be discussed.

5.1 UNCERTAINTIES IN THE ANALYSIS

In the evaluation of the increased maintenance due to redundancy of machinery systems it was assumed that only the ME, steering gear, and rudder arrangement was duplicated. This may seem to be a somewhat crude assumption. As described in section 1 it is a commonly held view that more redundancy is needed on a UMS but to which degree is not certain. Analyses of which modifications specific machinery service systems for a CMS would need, if they were to be used on a UMS, have been made by Abdelmoula et al. (2017) and Eriksen et al. (2021). A complete analysis of all the machinery systems of a proposed UMS, however, would require a very detailed and specific description of all the functional and operational requirements of the ship and its machinery systems. Even if such a description existed, the outcome of the analysis would still be contingent on many assumptions and on many factors that are not fully known or understood. An analysis would, for example, need reliable failure rate data for all the needed equipment units and a complete understanding of the effect of increased redundancy on the maintenance workload. The outcome of the analysis would also depend on subjective choices on acceptable risk standards for example. The analysis in this paper is intended to be broadly applicable to large oceangoing cargo ships, rather than a specific analysis of one individual ship. Proposing a design of a UMS in enough detail to which a detailed analysis of exactly which components would need to be duplicated is outside the scope of this paper.

On the one hand, the assumption made about the additional needed redundancy on UMS may overestimate the increased maintenance workload and, on the other, it might underestimate it. The propulsion power of each engine on a twin-engine ship would typically be less than that of a single engine on an otherwise comparable one-engine ship. Two smaller engines will require more maintenance than one large engine but probably not twice as much as is assumed. The assumption that there is no increased redundancy in any of the sub-systems on which the ME depends or in any of the many other machinery systems onboard is, on the other hand, likely to underestimate the maintenance workload. The assumption is a simplification and there would very likely be a need for increased redundancy of some equipment units within these systems (Abdelmoula et al. 2017; Eriksen et al. 2021). The extent of this redundancy is, as explained earlier in this section, highly speculative. Another factor that may contribute to the underestimation of the workload on UMS is that the additional equipment needed for remote and/or automated operation is not included. There are many systems on a CMS that require physical operation in some form, such as the opening and closing of valves, reading of manual gauges or the operation of local controls. Compared to a CMS a UMS would require many more actuators and much more remote monitoring and control equipment. This would contribute to further increasing the maintenance workload.

Besides the required equipment on UMS the maintenance strategy may also impact the maintenance workload. Unmanned operation may necessitate the use of more preventive and predictive maintenance (Jokioinen et al. 2016). This could have both positive and negative effects on the maintenance workload. A deliberate run-to-failure strategy (Moubray 1997) is often used for smaller and/or already redundant equipment units or part of units on CMS. Run-to-failure may not sound like an appropriate approach but for units or parts where the occurrence of a failure cannot be reliably predicted by the age or running time of the unit and where failures does not result in significant collateral damage or interruptions to the operation it ensures the utilization of the full service life of the unit or part. On a UMS equipment cannot be allowed to run-to-failure in the same degree because there is nobody around to repair it and the unit would have to remain in a failed state until the vessel could be accessed in the next port. To this effect it would likely be necessary to utilize more preventive maintenance, condition monitoring and predictive maintenance. A more conservative time-based preventive maintenance approach could contribute to increasing the maintenance workload on a UMS. Condition monitoring on the other hand may help to reduce it. Used correctly, condition monitoring can reduce collateral damage to equipment, avoid unnecessary maintenance and lessen the need for unplanned operation stops (Deighton 2016). Condition monitoring and predictive maintenance, however, does not prevent failures; it only detects failures or potential failures. Yet again the additional sensors needed for condition monitoring on UMS can also fail and will thus require maintenance. No matter the impact of a changed maintenance strategy on UMS it is important to note that this strategy could just as well be applied on a CMS. Unmanned operation may necessitate more condition monitoring and predictive maintenance, but it does not enable it in any way.

Another assumption made was that the proportions between the types of maintenance work; PM recorded, PM not recorded, and unplanned maintenance presented in section 4.1 apply equally to all categories presented in section 3.2.1 as well as to the additional maintenance resulting from increased redundancy. This may not be accurate. The analysed PMS data is weighted towards the mechanical systems which require more recorded planned maintenance and unplanned maintenance than unrecorded planned maintenance. More of the unrecorded planned maintenance, such as painting and chipping, is related to the structure of the ship, which is not specifically addressed in this analysis. The potential uncertainty resulting from this assumption is assessed to be minor because the relative changes to the maintenance workload, as seen in Table 6, are relatively small in both unmanned cases and because it influences both the identified increases and decreases to the maintenance workload similarly.

The analysis in this paper is based on a substantial amount of data but it would have further strengthened the study had maintenance data from more ships and/or different types of ship been available. Data for the analysis in this paper all originated from gas tanker vessels. This type of ship is not likely the most suitable for unmanned operation because of the hazardous nature of the cargo and the complexity of the cargo handling. The machinery system set-up, size and complexity are, however, not significantly different from that of many other types of large cargo ships such as oil/chemical tankers, bulk carriers or container ships. The findings in this paper are therefore applicable to a large group of commercial cargo ships. It must be considered, however, that there can be large variations in the maintenance workload based on size, trade and age of the individual ships.

5.2 MAINTENANCE WORKLOAD ON UMS

The analysis in this paper shows that the workload required for maintenance of large commercial cargo ships is considerable and that the impact of unmanned operation on this is relatively small. For both the unmanned cases the difference in the total maintenance workload is in the one-digit range. The analysis further shows that more than 40 per cent of the total work time onboard is used on maintenance. With only slight changes due to unmanned operation this proportion of the crew costs can be expected to remain largely unchanged on UMS and cannot therefore be counted towards potential savings for the unmanned operation of ships.

In case 1 in the present paper, it is assumed that the maintenance can only be done when the ship is in port and the constant work of 10.8 people would therefore be needed to handle the workload. Having 10.8 people working simultaneously in the engine room is realistic, it is after all not much more than the normal engine crew. It would, however, require the ship to be maintained at every port of call. Many bulk and tanker terminals are situated in remote areas where such maintenance services might be difficult to sustain. If the ship is only to be maintained at every other port of call, for example, the number of people working on many different equipment units simultaneously might begin to be problematic.

The calculated number of people of 10.8 is also only a theoretical minimum because it would not be possible to utilize the full time in port and plan work precisely to utilize the whole period. The duration of maintenance tasks may not be possible to predict with certainty in many cases. Care must be taken not to start tasks that cannot be completed before planned departure so as not to delay the operation. This issue is made worse by a large variety and uncertainty of the length of port calls on many types of ships.

Beside doing maintenance in port as assumed in the present paper, it may also be possible to maintain ships while they are at anchor as assumed by Kretschmann Lutz et al. (2015) in their economic analysis of a proposed unmanned bulk carrier. Much of the crew change, delivery of stores and bunkering occurs at anchor on CMS today. The logistical challenges of getting maintenance personnel and equipment onboard a ship at anchor are, however, greater than if it is in port. Anchorages for large commercial ships are often miles from shore. If people are to work on the UMS at anchor for extended periods there must also be some form of rudimentary accommodation systems such as heating, air-conditioning and toilet system on board, which would again add to the maintenance workload. Alternatively, there could be a system of service/accommodation ships or platforms perhaps in connection with a fleet of smaller crew transfer vessels, such as those used for offshore windfarms. This would of course also incur an additional cost on its own.

There is no doubt that the uncertainties described in the present section influence the accuracy of the analysis made in this paper. The factors influencing the maintenance workload do not exist in a vacuum but are coupled to many other factors. It may be the case that unmanned operation necessitates a different form of operation of UMS than CMS and that machinery systems would therefore be radically different. It is also possible that more reliable and perhaps simpler machinery systems could be used if the use of conventional systems are shown not to be practically feasible on a UMS. The benefits of these systems on the maintenance workload and reliability must of course be balanced with cost and with their effects on energy efficiency. It is again important to stress that all these potentially simpler, more reliable and less maintenance demanding systems could equally well be used on a CMS as on a UMS. The unmanned cases presented in this paper and the analysis of the total maintenance workload should not be taken as a depiction of a machinery system set-up of UMS and the maintenance that this would require. Rather, the results should be used as an indication of the gap between the present state of maintenance of cargo ships and what would be required for unmanned operation in the future. Because the same mechanisms with which the maintenance workload could be reduced on a UMS could equally well be used on a CMS the proportions of the reduced maintenance due to unmanned operation versus increased maintenance due to increased redundancy can largely be expected to remain unchanged even if the total maintenance workload changes.

6 Conclusion

In this study the impact of unmanned operation on the workload required for the maintenance of commercial cargo ships is explored. Data on Planned Maintenance, the work time distribution of the crew and the operation of the ships originating from five vessels is analysed. Two unmanned cases are studied: case 1 one where the ship is always unmanned at sea and case 2 where the ship has the option to periodically accommodate a crew during sea passages. The two unmanned cases are compared to a base case of conventionally manned operation.

The study finds that elimination of the systems and equipment needed for the accommodation of the crew in case 1 can reduce the maintenance workload by 18 per cent and an additional 3.8 per cent of the work can be moved from the ship to shore. In case 2 where the systems and equipment needed for the accommodation of the crew are reduced but not eliminated, the reduction in the maintenance workload is 10 per cent and only 0.4 per cent can be moved to shore. On the other hand, it is found that the increased redundancy of machinery due to the severely restricted possibility of doing corrective maintenance onboard during unmanned operation will contribute to an increase in the maintenance workload of 14 per cent. This increase will apply in both case 1 and case 2 because the ship must be able to operate unmanned.

The total change in the total maintenance workload when both the work that must be done onboard the ship and ashore is considered amounts to a reduction of 4 per cent for case 1 but an increase of 4 per cent for case 2. Overall, it is found that the impact of unmanned operation of ships on the maintenance workload is minor. The elimination or reduction in the need for maintenance of the accommodation systems and safety equipment due to unmanned operation can reduce the maintenance workload. This saving can, however, easily be equalled or even exceeded by the increased maintenance workload resulting from increased redundancy.

The analysis shows that the workload relating to maintenance of commercial cargo ships is considerable. For the five ships analysed in this paper an average of 14,311 man-hours was spent on maintenance per year per ship for the base case, which is equivalent to the full-time job for 8.3 people. The analysis also showed that 43 per cent of the total onboard workload for the operation of the five ships was used on maintenance. This workload will remain largely unchanged regardless of unmanned operation and the cost of this work cannot be counted towards potential savings in crew costs on unmanned ships.

The magnitude of the workload may be problematic in the operation of unmanned ships if it is not to interfere with the normal operation of the ship. If, as assumed in case 1, the ship is to be maintained only in port, which in the analysis of the five ships is found to be 14 per cent of the operating time, it would require 10.8 people to work around the clock. Whereas it would per se be realistic for 10.8 people to work simultaneously onboard the ship, it may not be possible for the ship to be maintained at every port. There is a practical limit to how much work can be done at the same time, which may be a challenge if too much maintenance work accumulates because the ship cannot be maintained in several consecutive ports.

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Appendix A

This appendix details the procedure of categorization of the maintenance jobs as briefly introduced in section 3.2.1 of the main text and gives a comprehensive description of the maintenance job categories.

The equipment/maintenance jobs are assessed as they are found in the PMS data. In section 3.2.3 of the main text it is described to what extent particular jobs categories are included in the unmanned cases, but no assessment is made in the categorization described here as to whether the ship could be designed in a way where this particular equipment/ maintenance job would not be needed. Systems such as the freshwater system, which is used both for the accommodation of crew and for the operation of the ship, are generally considered to be unchanged even if unmanned operation may allow the capacity of the system to be smaller. Individual components or maintenance jobs regarding the systems, such as the ultraviolet filter, hot water calorifiers or the testing for bacteria in the case of the freshwater system, may however be evaluated not to be needed on the unmanned ship.

Equipment with multiple functions across categories such as “provisions/MOB handling crane” goes into the most safety critical category.

The Air Conditioning unit for Engine Control Room is included because it provides cooling for the main switchboard.

Job category descriptions

Crew equipment
Equipment exclusively onboard for the accommodation and/or comfort of the crew, such as air-conditioning, toilet systems, provision refrigeration, galley, and laundry equipment, etc. As it is assumed that there is no accommodation structure for fully unmanned operation, equipment such as “fire doors in accommodation” also falls into this category.

Ship equipment
Equipment for the operation and propulsion of the ship such as for propulsion, power generation, cooling, heating, cargo handling, steering, navigation, etc.
Many systems or equipment units in the case study require manual operation in their present form. It may not make sense to use these specific units in their present designs on an unmanned ship but what is considered here is whether the function of the unit or system is used for the operation of the ship.

Lifesaving appliances
Equipment for the rescue and evacuation of people onboard, such as lifeboats and MOB boats and equipment, pyrotechnics, and portable communication equipment such as handheld VHFs, EPIRBs, SARTs, etc. Also included in this category is ship hospital equipment.

Manual firefighting equipment
Firefighting equipment which must be manually handled, carried, and operated and which cannot realistically be made to work remotely, such as fire hoses, fire blankets, portable fire extinguishers, breathing apparatuses, etc.

Automatic firefighting equipment
Automatic/permanently installed firefighting and fire suppression equipment such as CO_2, hot foam, water-mist, fire doors, emergency stops, quick release valves, etc. which may or may not require manual activation on the manned ship, but which could conceivably be made to operate remotely or automatically. This category also includes fire detection equipment. Firefighting equipment exclusively used in the accommodation area belongs in the “crew” category.

Tools
Tools needed for maintenance and/or inspection tasks on the ship but which require human operation, such as lathes, bench drills, welding equipment, special tools, oil or water testing equipment, manual tank level gauging equipment, etc.
Consumables such as oil, grease, chemicals, paint, etc. are also included in this category along with the equipment specific to the storage of this onboard such as ventilation and firefighting equipment for paint, oil, and chemical lockers.
This category also includes equipment for the boarding and disembarkation of the ship, ship security (ISPS) equipment, oil/chemical spill (SOPEP/SMPEP) equipment, and work-related personal protection equipment.

Navigation and manoeuvring equipment
Screens, readouts, operation handles, buttons, etc. for the navigation and manoeuvring of the ship, which require manual operation and would be placed in a shore-based remote-control centre instead of onboard the ship if operation is unmanned.
Radar antennae, navigation lights, radio antennae that must be physically on the ship belong in the "ship equipment" category and are not included in this category.

Communication equipment
Radio and satellite communication equipment and internal ship communication equipment.

APPENDIX B

In this appendix a detailed description is given of the unmanned cases introduced in brief in section 3.2.3 of the main text.

Case 1: In this scenario the ship is always unmanned at sea and there is no possibility for accommodating people onboard. All maintenance is done in port and all workshop equipment, special tools for maintenance and consumables such as spare parts, oil, grease, and chemicals are stored ashore. The engine room crane is, however, assumed to still be onboard as it is an essential but stationary piece of equipment. All access to the ship must be by external gangways or ladders. The ship is only physically accessible in port and can only be accessed at sea in emergency situations. In case 1 there is no accommodation structure on the ship but, as the ship must be accessible for maintenance in port, amenities such as lighting, power, water, compressed air, etc. must be available in the engine room and on deck and are assumed to be identical to the base case. Sensors on machinery equipment, fire, and bilge alarms, etc. must also be onboard and is to be identical to the base case. Some of the manual firefighting equipment such as fire extinguishers must also be onboard. It is assumed that 50 per cent of the manual firefighting equipment of the base case is onboard. All the automatic firefighting equipment must be onboard. As the ship is not to be navigated and operated manually onboard there will be no need for the display and operation part of the navigation and manoeuvring equipment onboard. The transmitter/receiver part of equipment such as radars or echosounders, however, must still be onboard. Equipment that is onboard and is manually operated today but must be assumed to also be onboard in a remotely operated version, such as HF radio, search light, signal lamp, etc. is included in case 1. It is also assumed that mooring equipment such as winches, ropes and wires are onboard the ship.

The jobs relating to the maintenance of tools, consumables, and the display and operation part of navigation and manoeuvring equipment do not have to be carried out onboard but must then be carried out ashore instead.

Case 2: In this scenario the ship can operate unmanned, but repair crew can do maintenance onboard the ship during sea passages. The same maintenance jobs are included in case 2 as in case 1 except for the following differences.
Equipment enabling the accommodation of the repair crew and lifesaving appliances must be present, but it is assumed that the equipment and the maintenance workload related to it can be reduced by 50 per cent compared to the base case. Since maintenance work is done onboard the ship during sea passages the workshop equipment, special tools, and consumables must be onboard. All the manual firefighting equipment in the engine room and other machinery spaces must be onboard as in case 1, but some additional equipment is needed in case 2 for the accommodation. It is assumed that 75 per cent of the manual firefighting equipment of the base case is needed in case 2.

Paper VI*

Eriksen, S.; Lützen, M. **Manning the unmanned ship: Is safe manning legislation a bottleneck in the development of autonomous ships?** *(Submitted 29 May 2021) SN Social Sciences*

**Appended as submitted in content but reformated for readable and uniform presentation*

Manning the unmanned ship: Is safe manning legislation a bottleneck in the development of autonomous ships?

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ABSTRACT

Legislation is often mentioned as a barrier to the development of autonomous and/or unmanned ships. Fully unmanned operation may not be possible within the current rules, but it is not so clear whether the laws on safe manning of ships is currently a bottleneck in a gradual reduction of crew sizes. This paper examines this issue through the analysis of data on safe manning and actual manning for 210 cargo and passenger ships. It is found that most vessels have an actual manning which is significantly higher than the minimum manning required by law. Both safe and actual crew sizes are, as expected, found to increase with increasing ship size but so is the difference between safe and actual manning. The reason why ships operate with a larger crew than required by law is found to be caused by the technical and operational needs of the vessels. Maritime law may not at present allow for completely unmanned operation of commercial cargo ships. If the assumption that the reduction in crew size will happen gradually is accepted, however, legislation on safe manning is not a bottleneck in the development of autonomous and unmanned ships.

KEY WORDS

Autonomous ships; Unmanned ships; Manning; Safe Manning; Legal barriers

1 INTRODUCTION

If commercial cargo ships can be made to operate unmanned and/or autonomously it would have the potential to fundamentally transform the maritime transport industry. Fully unmanned operation would eliminate the need for an accommodation which would allow for an increase in cargo capacity and improve the energy efficiency due to reduced wind resistance (Kobylinski 2018). The most obvious and an oft-mentioned expected benefit of unmanned operation, however, is a reduction in crew costs (Hogg and Ghosh 2016). There are drivers behind unmanned operation such as improved safety through the removal of humans from a dangerous working environment and a reduction of human operator errors which are not directly linked to cost reductions. There is little doubt, however, that the main driver behind the

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development of unmanned ships is the economic aspect and that most of the expected cost reductions are linked to the elimination or reduction of the crew.

It is still uncertain which proportions of the work tasks required to run a commercial cargo ship would be possible to automate, which would disappear with unmanned operation, which could be moved ashore, and which would still need to be physically done onboard. It is therefore also still uncertain what the potential for a reduction in crew costs will be for unmanned operation. What is certain is that crew costs constitute a significant proportion of the running costs of ships for most ship types (Kretschmann et al. 2015). A reduction in the crew costs through the elimination of the crew or a reduction in the crew size therefore presents a significant economic incentive to ship owners. For the present, however, fully unmanned operation is a step too far for most (World Maritime News 2018b, 2018a). Many view autonomous operation of large commercial cargo ships as a gradual development where more and more work processes move from human to automated control (Faivre 2019; Petersen 2019; Eystø and Meling 2019). It is a commonly held view that the reduction in crew sizes resulting from this will be incremental rather than a sudden shift to fully unmanned operation. It is also widely recognised that there are many barriers to unmanned or autonomous operation of ships in the existing maritime laws and regulations.

Several studies have investigated the issue of potential barriers to unmanned and/or autonomous operations of ships in maritime law from several different perspectives. Carey (2017) investigates where the laws of the sea demand a human presence on-board a ship. The paper considers how the autonomous and/or unmanned ship can comply with the obligation to be seaworthy, safe manning levels, the duties of the shipmaster and compulsory pilotage. Van Hooydonk (2014) explores whether existing public and private maritime laws can in principle still be applied to unmanned ships and examines which existing rules will require amendments and which new rules might have to be developed. A comprehensive examination of barriers in the maritime laws and regulations arising from the introduction of autonomous and/or unmanned ships has been done by the Danish Maritime Authority (2017). Decetelaere (2017) examines whether the international conventions related to maritime law will present a challenge for unmanned ships and how unmanned ships can comply with the rules of these conventions. Lee (2016) considers the restructuring of shipowners’ liability due to the introduction of unmanned and/or autonomous operation of ships from a Scandinavian shipowner perspective.

Maritime law in general does not accommodate for unmanned operation of ships (Carey 2017). Even though the idea of unmanned operation is not new (Bertram 2003), it has not yet been technically and commercially possible to apply this mode of operation in commercial shipping. The presence of an onboard crew is deeply imbedded in most maritime legislation. In some places, the presence of an onboard crew is explicitly required but more often it is simply presumed. There are important issues for unmanned operation regarding seaworthiness, contractual liability and obligations of an unmanned ship towards other ships which existing maritime law does not accommodate for (Danish Maritime Authority 2017). The consensus is that changes to most parts of maritime legislation will be necessary to allow for the operation of autonomous and/or unmanned ships. There is also a general agreement, however, that maritime law will be able to accommodate these changes.

Whereas it is evident that fully unmanned operation of commercial cargo ships is problematic within present law, it is not so clear the extent to which existing maritime legislation is a barrier in the gradual reduction of crew sizes. This paper will investigate this issue by comparing actual crew sizes to the minimum crew sizes specified in the safe manning documents for a large group of ships. By analysing this manning data and through interviews with relevant industry representatives, this paper will explore which factors influence the actual and safe manning levels and the possible difference between the two. The paper will further examine the extent to which it would be possible to further reduce the actual and safe manning levels.

2 METHODOLOGY AND DATA

Both quantitative and qualitative data is used in the analyses in this paper and therefore a mixed method approach is used (Creswell and Clark 2017). The main emphasis is on the quantitative data and the results of the analysis of this data. The qualitative data is used to further explore the results of the quantitative data. A so-called sequential explanatory approach is used (Creswell and Clark 2017). This method can also be designated QUANT → Qual, signifying the emphasis on the quantitative data and showing the sequence with the quantitative data first followed by the qualitative data.

2.1 QUALITATIVE DATA

The qualitative data consists of three semi-structured expert interviews. The expert interviewees were Crewing Manager from the Danish shipping company Lauritzen Kosan (CM1); Crewing Manager from the Danish shipping company TORM (CM2); and Manning Adviser from the Danish Maritime Authority (MA). The shipping company Lauritzen Kosan operates a fleet of about 25 gas tankers of sizes between 4,000 and 10,000 Gross Register Tonnage (GRT). TORM operates a fleet of roughly 75 product oil tankers of between 25,000 and 65,000 GRT. Both companies operate with crews of mixed nationalities and their ships trade worldwide.

The interviews followed an interview guide and the questions revolved around the following themes: How is the safe and actual manning level determined? What impacts the crew-sizes? Is there a difference between the safe and actual manning level and why? Will the crew sizes decrease in the future and which political/technical/other measures must be in place for that to happen? Questions were also asked about crew costs and the expert opinions of the interviewees on the potential/feasibility of unmanned operation of cargo ships. The interviews were conducted between August and October 2019. The duration of the interviews was between 45 and 90 minutes, they were conducted in Danish and the audio from the interviews was recorded. Notes were taken during the interviews and on the basis of the recordings. Any direct statements from the interviews used in the text have been translated from Danish and paraphrased for a more precise wording by the authors. Besides serving to further explore the results of the analysis of the quantitative data, the interviews also provide background for how safe manning and actual manning levels of ships are determined as described in section 3.

2.2 QUANTITATIVE DATA

The quantitative data consists of data on safe manning levels and actual manning levels of ships. None of this data is publicly available information nor do centralized repositories containing this data exist. Six Danish shipping companies were willing to share data on safe and actual manning for use in the present analysis. To attain a larger dataset than that made available from the shipping companies, additional data on safe manning was requested and granted from the Danish Maritime Authority (DMA), see Figure 1. Information about the actual manning for the same ships was granted from the Danish Navy Command, which operates the Vessel Traffic Service (VTS) in the Great Belt region of Denmark, one of the two main shipping routes for large ships passing in and out of the Baltic sea. Figure 1 shows the origin and proportion of data received from the shipping companies and the VTS/DMA, respectively.

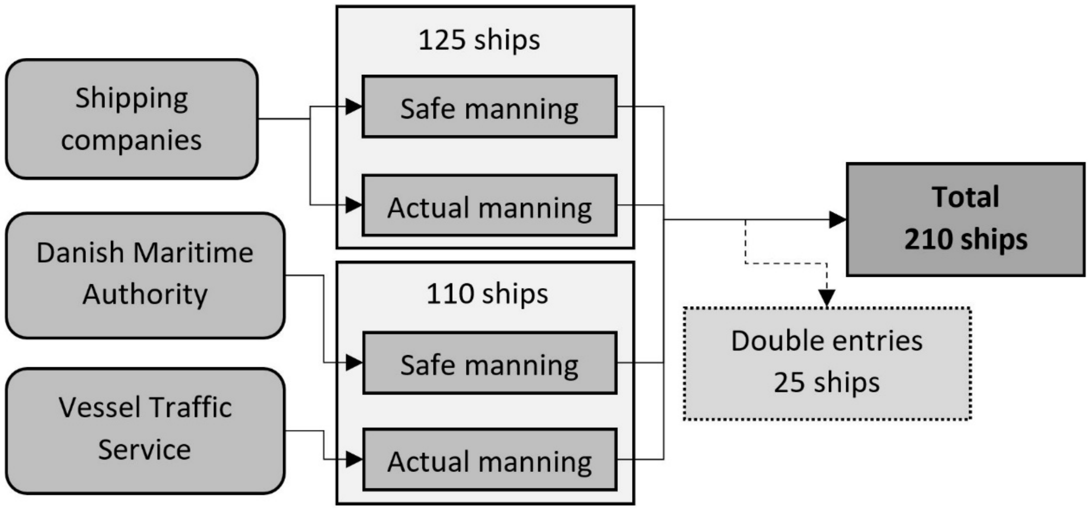

Figure 1 Origin of quantitative data used in the present analysis

Ships passing through the Great Belt region must report certain information to the VTS, such as the number of People on Board (POB). A list containing the POB of all cargo and passenger ships which have passed through the reporting area and reported to the VTS in a period of one year between 1 July 2018 and 31 May 2019 was requested and granted access to. Ships of all nationalities report to the VTS but because the data was to be correlated with safe manning data from the DMA, which is restricted to Danish-flagged ships, only data on Danish ships was requested. If a ship had reported to the VTS more than once within the specified time period and if the ship had reported different POB numbers, the lowest number was used in the analysis.

The 110 ships for which data was supplied from the VTS/DMA, as seen in Figure 1, are all under the Danish flag. The 125 ships for which data was supplied from the shipping companies, also seen in Figure 1, are all managed from Denmark but 60 of them are non-Danish flagged ships. These ships are registered under the flags of the United Kingdom, Malta, Antigua and Barbuda or Singapore. There were, as Figure 1 shows, 25 double entries between the ships for which data was supplied from the companies and the ships were also found in the VTS/DMA list. The smallest actual manning of the double entry values was used and the other was removed from the list. Of the total 210 ships, as seen in Figure 1, 150 are under the Danish flag. Supplementary information such as GRT and ship dimensions for these ships was found in the Danish Ship Register and, for the ships not under the Danish flag, from public AIS data (DMA; MarineTrafic 2021).

3 MANNING LEVELS OF SHIPS

3.1 SAFE MANNING

It is the responsibility of each state to ensure that all ships registered under their flag are safely manned. All ships for which the laws of their respective flag state apply must carry a Minimum Safe Manning Document. The document contains information about the number of crewmembers required for the safe operation of the vessel and information about the qualifications needed for each individual crewmember. The laws on manning of ships are not fully internationally standardised, but many governments have fully or partly incorporated the guidelines of IMO resolution A.1047(27) IMO (2011) into their national legislation. According to interviewee MA, safe manning was previously based on the so-called scale manning principle where minimum crew size was rigidly based on the size and propulsion power of the ship. Many countries have now adopted the goal-based approach detailed, for example, in IMO resolution A.1047(27). The goal-based approach requires an individual evaluation of each ship with regard to, for example, ship type, construction and equipment of the ship, level of automation, cargo to be carried and trading area. Compared to the scale manning principle, the goal-based approach is much less rigid and leaves a lot of room for interpretation by the individual administration (MacDonald 2006). The Danish law on the manning of ships, for example, which has largely adopted the guidelines of IMO resolution A.1047(27), is a so-called framework law which only lays down general principles but leaves it up to the administration to enact the further legislation and other specific measures (Danish Maritime Authority 2012). Only one crewmember is specifically required in the law, namely the master. The law then describes in goal-based terms that the ship must be manned in such a way that makes it possible to cover all tasks of importance for the safety of the ship and those on board, including (Danish Maritime Authority 2012):

- maintenance of safe watchkeeping on the bridge and in the engine room
- operation and maintenance of lifesaving appliances
- operation and maintenance of damage control equipment, fire-fighting equipment and communication equipment
- other safety-related maintenance and cleaning activities
- mooring operations
- food provisioning and sanitary conditions.

Other legal instruments, such as the Maritime Labour Convention (ILO 2006) or the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, STCW (IMO 2017), then specify, for example, what safe watchkeeping entails and the required training of the crew undertaking it.

A shipowner must apply for a Minimum Safe Manning Document from the respective flag state under which they wish to register the ship. If the ship is registered in Denmark, the procedure, according to interviewee MA, is that the shipowner describes the intended operation of the vessel in order for the DMA to be able to make their assessment. The shipowner must also suggest a safe manning level which the DMA can modify or accept. There is a lot of room for interpretation of the rules on the side of the administration, but they also rely heavily on previous decisions for other similar ships. If the safe manning of a new ship is to be different than that of other similar ships, the shipowner must justify which measures or technical advancements makes this possible. The application of the safe manning itself follows a standard form, but according to interviewee CM1, there is typically also a dialogue between the administration and the shipowner in which a common understanding is reached.

Flag states compete to attract tonnage to their registers and according to MacDonald (2006), this is one of the key reasons why the safe manning has reached such low levels today. In the competition for tonnage, there are of course also other important factors such as quality, costs and level of service. Flag states which ships do not live up to the safety standards or repeatedly violate the rules in other ways are grey or blacklisted (Paris MoU 2020). Ships under these substandard flags are more heavily scrutinised and may be barred from competing for certain charters. The tanker segment, in which both the interviewed companies trade, is very safety orientated and is especially critical of this issue. If the companies want to be able to trade with the major oil, gas and chemical companies, they are effectively restricted to the use of the higher quality flags according to interviewee CM1. Both companies interviewed in connection with the present analysis acknowledged that manning levels are a factor in their choice of flag but also explain that the difference in manning between the flags under which they register their ships is minor. Their choice of flag is more focused on commercial considerations and the flexibility and overall service level of the flag state administration.

3.2 Actual manning

There may be regional or national rules that require additional crew onboard apart from those listed in the Minimum Safe Manning Document but in general this is rare according to interviewee CM1. Countries rely on international trade and are legally or commercially required to accept the entry of foreign ships and to recognise the rules of their flag state including safe manning.

Safe manning forms the basis of the actual manning level, but the shipowner may choose to operate with a larger crew. The actual manning level is not static but may change due to the trade pattern of the ship, major maintenance work and the age of the vessel. Neither of the interviewed companies have a formalised system for the upscaling or downscaling of the crew. The initial manning on a new ship mostly relies on experience according to interviewees CM1 and CM2. The company may err on the side of caution in the beginning and scale down later. Subsequent changes to the crew size happen based on the immediate needs of the operation and are decided in cooperation between the ship and the technical and commercial department ashore.

4 Analysis and results

In this section, the data introduced in section 2 is analysed. Section 4.1 presents the analysis and results of the quantitative data on crew sizes. In section 4.2, the special case of Ro-Ro passenger ships is further investigated, and in section 4.3 the results are qualified based on the three interviews described in section 2.1.

4.1 Quantitative analysis and results

The distribution of the ship types used in the present analysis is seen in Table 1. Figure 2 shows the distribution of ship types globally based on data from UNCTAD (2020). It is clear that the data used for the present analysis does not perfectly represent the global fleet. Even though the categories of the data used in the present analysis and categories of the UNCTAD data are not identical, it is obvious that bulk carriers and general cargo ships, for example, are underrepresented in the present analysis compared to the global fleet. Chemical tankers are part of the 'Other types of ships' category in Figure 2 whereas they are grouped together with oil tankers in Table 1. Therefore, oil and chemical tankers cannot be directly compared, but it is still clear that this segment is overrepresented in the data used for the present analysis. Possible uncertainties arising from the imbalance in the dataset are further discussed in section 5. Despite differences in the distribution of ship types, it is assessed that the results of the present analysis are applicable for commercial cargo ships in general. It is clear, however, that the results are more representative of some ship types than others.

Table 1 Ship-types in dataset

Ship type	Number of ships in data	Per cent of total
Bulk	2	1%
Container	19	9%
General cargo	16	8%

Gas tanker	25	12%
Ro-Ro Passenger <1000GRT	8	4%
Ro-Ro Passenger >1000GRT	6	3%
Oil/Chemical tanker	130	62%
Ro-Ro cargo	4	2%
Total	210	

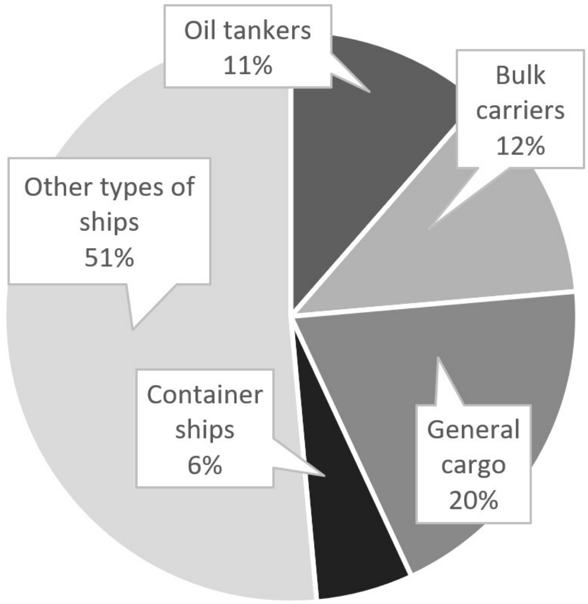

Figure 2 Distribution of ship-types globally 2020 (UNCTAD 2020)

Figure 3 Shows the distribution of the difference in per cent between the safe manning level and the actual manning. Out of the 210 ships in the analysis, only 6 were operating at minimum safe manning. The remaining 97% had a larger crew than required by legislation. 78% of the ships had an actual crew size that exceeded the safe manning by 33% or more, and on 49% of the ships it exceeded the safe manning by 50% or more.

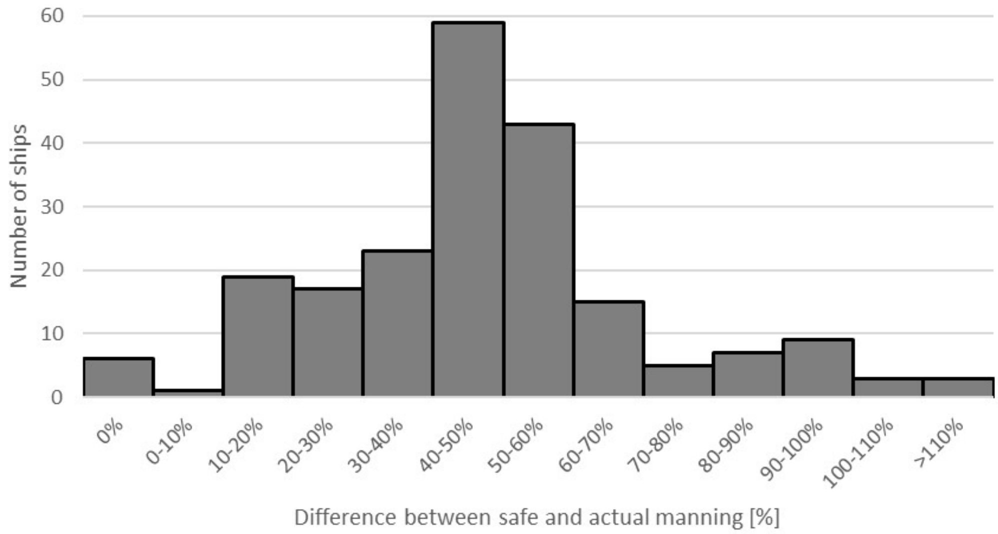

Figure 3 Distribution of difference between safe and actual manning in percent across all ships in data

Figure 4 shows the minimum safe manning and the actual crew size plotted in relation to ship size in GRT. The data is plotted with a logarithmic x-axis to best illustrate the distribution. The trendlines for the safe and actual crew sizes are shown to indicate the general tendencies but they do not imply a specific mathematical relationship between ship size and crew size. Actual manning levels are not lower than safe manning for any of the analysed ships despite what is indicated by the trendlines below 1000 GRT.

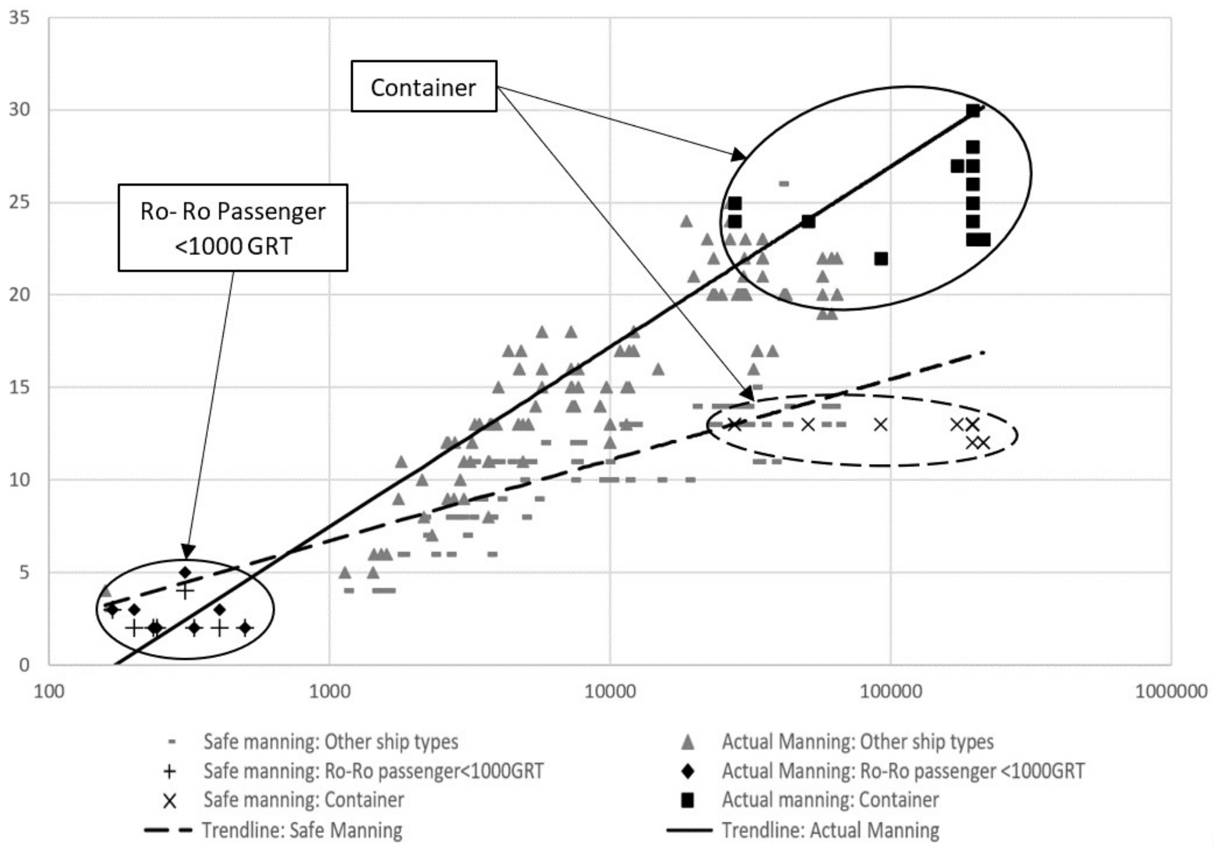

Figure 4 Actual and safe crew size in relation to ship size in GRT

The two categories of containerships and Ro-Ro passenger <1000 GRT are highlighted in Figure 4 because they represent the two extremes on both the ship and crew size spectrum. There are single ships in the Ro-Ro passenger >1000 GRT category with crew sizes of more than 150, thus exceeding that of containerships. In fact, three ships in the Ro-Ro passenger >1000 GRT category are outside the plotted area in Figure 4 because the crew sizes on these are much larger than the rest of the ships in the analysis. The Ro-Ro passenger >1000 GRT category, however, is very heterogeneous and only contains six ships, as seen in Table 1. The special case of Ro-Ro passenger ships is further described in section 4.2.
Containerships is the category, apart from Ro-Ro passenger >1000 GRT, which has the largest actual crew sizes and the largest difference between minimum and actual crew size. The smallest actual crew sizes across a category are found in Ro-Ro passenger <1000 GRT, which also have the smallest difference between minimum and actual crew size. Containerships and Ro-Ro passenger <1000 GRT are also the groups with the largest and smallest vessels across the groups, respectively.

Not surprisingly, Figure 4 shows that there is a strong correlation between both minimum and actual crew sizes and the ship size. From the trendlines, it is also seen that the gap between minimum and actual crew size increases with ship size as well. The difference between safe and actual manning increases with increasing ship size in both absolute and relative values. Containerships have between 10 and 17 crewmembers more than the safe manning requires, with an average of 12, or between 69% and 131% with an average of 95%. At the other end of the spectrum, six out of the eight ships in the Ro-Ro passenger <1000 GRT category have no more crew members than required by the safe manning and the remaining two have only one additional crewmember. For large ships, a significant difference between safe and actual manning is the norm, not the exception. Ships of 10,000 GRT or over constitute 61% of all ships in the analysis. All the ships in this group have a larger crew than required by law, for 95% of them the difference between actual and safe manning is 33% or more and for 66% of the them the difference is 50% or more.

4.2 RO-RO PASSENGER SHIPS

Ro-Ro Passenger ships as a unified group across all sizes simultaneously have the smallest and the largest crews of all the ships in the analysed data. The smallest passenger ships in the data have crews of just two persons and the largest have crews of more than 150. Passenger ships make up eight out of nine ships with a GRT of less than 1,000 in the data. With only one cargo ship in this group, it is not possible to say with any certainty if it is the ship size alone or if it is the passenger operation that allows for such small crews. There are, however, factors relating to passenger operation which distinguish it from other ships. Many small passenger ships do not operate during the night, the crew works in shifts and does not stay onboard outside working hours. A ferry will typically have a very fixed schedule going between the same ports with dedicated berths which allows for a high degree of optimisation and standardisation of berthing and loading/unloading operations.

Passenger operation, on the other hand, also presents unique challenges relating to passenger safety and evacuation of the ship in case of emergencies, which affects the manning size. The crew on passenger ships are typically divided into an *operation crew* and a *safety crew* and on larger vessels there may also be a separate *maintenance crew*. The safe manning document may specify that the ship is not allowed to carry passengers or only allowed to carry a restricted number with the *operation crew* only. To carry more passengers, an additional *safety crew* must be onboard. There may be several of these defined maximum passenger steps in the safe manning document which allow the vessel to man up and down based on the needed capacity at the time. The *safety crew* are typically members of the catering and service crew who have received the necessary training to undertake such duties in case of emergency.

To further examine the issue of manning of passenger ships, an example of the manning of the vessels in the category Ro-Ro passenger >1000 GRT is investigated. Access to the manning schedule for one particular ship for one day in the low season was granted for use in the present analysis. The ship adjusts the manning size based on the expected number of passengers. For this particular ship, the required minimum manning changed 6 times in one 24-hour period and the actual manning changed 11 times. The manning level of some passenger ships can thus be much more dynamic than cargo ships. At no point in the schedule, however, was the actual manning level as low as the safe manning level. At the lowest, the difference between the two was 55% and at the highest it was 165%. The lowest manning level in the manning schedule was used for this ship in the overall analysis.

Even though the same distinction between *operation crew* and *safety crew* exists, passenger ships on longer routes obviously cannot adjust their crew size as dynamically as those on short routes. Like cargo ships, they will also have to accommodate off-duty crew onboard. Passenger ships on long overnight routes are those with the largest crews in this analysis. Unlike small passenger ships, they are not purely a mode of transport but typically also feature elements of leisure such as restaurants, bars and casinos, which require a high level of service and a correspondingly large staff.

4.3 QUALIFYING THE RESULTS

Both interviewees CM1 and CM2 point to crew costs as a significant financial expense constituting, as a rule of thumb, about 2/3 of the total operational expenses within their segments. The actual manning of all the ships of both participating companies was higher than the safe manning but as the interviewees explained, their manning levels or crew costs is not different than their competitors. There may be small variations in the number of officers versus ratings but there is little or no difference in the total crew size between competitors in their segments according to CM2. Both CM1 and CM2 agreed that there is a clear economic incentive for them or their competitors to reduce the crew size if possible. As to the question of why the crew size is not reduced, they both point to a lack of technical systems to support this.

Question: "*If there was a technical system which made it possible to reduce the crew, would there be an incentive within the business to implement it?"*
CM1: "*Yes, of course. If you could put some system out there and replace two crew members you would do it. But you can't, not with the way the ships are built today."*
CM2; *"Yes, of course there is… but unless someone reinvents the wheel that is not really an option."*

The interviewed crew managers did not see any other challenges, legal or otherwise, in the reduction in crew sizes within the boundaries of safe manning. CM1 explains *"We choose to have more crew onboard than what is required because we see a need for it"*. Neither the interviewees from the shipping companies or the DMA were aware of or saw the introduction of any new technologies that could reduce the manning level significantly in the near future and all shared the view that the reduction in crew sizes in the near future would be minor. MA states *"Maybe minor changes will happen… I don't think we will see it reduced to half, for example"*. In the further future, electronic lookout and periodically unmanned bridge was seen as something that could be used to reduce the manning levels. Both companies see the development going towards unmanned operation but perceive this as far off. CM1 explains *"What we are seeing now are very, very small steps. If we really are to move towards seeing unmanned operation, much bigger steps need to be taken"*. Neither interviewees see large cargo ships, especially those in the tramp trade, as being amongst the first where unmanned operation is introduced but point to small ferries instead.

Asked about if and why a small safe manning would be desirable if the actual manning is larger anyway, both interviewees CM1 and CM2 pointed to flexibility. MA did not perceive a strong pressure or strong wish from operators of large cargo vessels to arrive at small safe manning levels for their segments of ships. The strongest pressure for small safe manning sizes is in smaller ferries where the actual manning is close to the safe manning. MA explains *"on large ships a reduction in the safe manning is mostly theoretical, they can't reduce the actual manning anyway"*. The two interviewed companies did not think a reduction of the safe manning for their ships would be achievable without the implementation of technical systems which would allow for a reduction of the work burden onboard. If such systems were to become available in the future, however, the legislation does allow for further reduction in safe manning according to MA. For the present, the two companies did not think that their actual manning level and the compositions of their crew would be any different even if they could get a different safe manning.

5 DISCUSSION

Autonomous and/or unmanned operation of ships, as described in section 1, is projected to revolutionise the maritime industry and the main economic benefit is expected to come from the elimination of the crew. Even if fully unmanned operation is not technically feasible on all ship types, autonomous technologies are still projected to dramatically reduce crew sizes and the related costs (CNBC 2018). According to some, the technologies enabling this revolution are already here and what is holding it back now is mostly commercial issues and legal barriers (Willumsen 2018). There are undoubtedly serious legal barriers to unmanned operation, as described in section 1, but is the legislation actually a present bottleneck in the gradual reduction of crew sizes moving towards unmanned and/or autonomous operation?

If legislation is what is holding back a potential reduction in crew sizes, actual crew sizes should be found to be identical or close to safe manning sizes. As the analysis in section 4 shows, this is clearly not the case for the vast majority of ships. Ship owners or operators have a clear economic incentive to reduce crew sizes and there is nothing legally stopping them from doing so. The industry, however, does not share the view that technical systems are already available which would allow them to make such reductions in the crew sizes. The results of the analysis presented in section 4 show quite a clear difference between the safe and actual manning levels of most ships but there are sources of uncertainties which must be considered.

The comparisons between safe and actual manning levels in section 4 compare total crew levels. However, a safe manning document or an actual crew is not just a number and crewmembers are not all identical. The safe manning specifies how the ship must be manned in the bridge, deck, engine and galley/catering departments and the minimum required training each position must have. There may be cases where the safe manning specifies more crewmembers than needed for the operation in one department while the actual crew is higher than required by the safe manning in other departments. There is typically very little overlap in the qualifications of crewmembers of different groups and job functions can only be shared between departments to a limited degree. According to both CM1 and CM2, the size and composition of their crews would not be different even if the safe manning allowed for it, but it may be different in other segments of shipping. Especially on ferries where the *operation crew* is so separated from the *safety crew*, it makes sense to pursue a low safe manning for one department despite the actual crew greatly exceeding the safe manning in other departments. There are also great differences in the qualifications and salaries between the officers and the ratings. It may make financial sense to employ two or more ratings instead of one officer if possible.

There are also limitations in the validity of the data used in the analysis which must be considered. Data on safe manning of ships is unambiguous since it is determined by an authority, as presented in section 2.2, whereas the actual manning levels are much more dynamic. According to interviewees CM1 and CM2, at least a portion of the actual manning values used in the analysis originating from the shipping companies represents a “minimum operational manning” for the internal use of the company rather than the exact number of crewmembers onboard each ship at the time of data sampling. The shipping company may temporarily scale up the manning to meet the demands of the operation or there may be cadets or fitters onboard as supernumeraries. The actual manning levels may therefore be higher than the “minimum operational manning” given by some of the companies. On the other hand, actual manning levels may be lower than the POB values given in the part of the data used in the present analysis originating from the VTS. POB does not always correspond exactly to the ships’ actual crew size because it may include visiting repair personnel, relatives of the crew or others traveling with the ship who are not part of the crew.

The majority of ships in the present analysis are registered under the Danish flag. According to the two interviewed companies, there are only minor differences in the safe manning sizes between the flags that they register their ships under. There may, however, be other flag states where the safe manning levels are different from these. According to interviewee MA, the safe manning sizes under the Danish flag is on the lower end of the spectrum.

The results of the analysis are considered to be applicable for larger cargo ships in general, but some ship types are better represented in the data than others. The majority of ships in the present analysis are under the Danish flag, which concentrates more on high-value vessels such as tankers. Bulk carriers and general cargo ships are greatly underrepresented and there is a complete lack of some types of ships in the data such as cruise and supply ships. Data from the VTS/DMA only originates from Danish ships passing through the Great Belt region, which is not a perfect representation of the global fleet. The composition of the ships within each ship-type category may also not fully represent the global fleet. The containership category, for example, is heavily dominated by a group of 15 super large ships with a length of nearly 400m, which is not representative of the world fleet of containerships.

Considering the sources of uncertainty discussed here, it is possible that the exact results of the quantitative analysis would have been different had some ship types had been better represented, had more ship-types been included in the data or had the number of ships under non-Danish flag been accessible. It is believed, however, that these potential differences are minor and that they would not have changed the overall findings of the present analysis.

The results show that a reduction in the crew size is possible within the existing safe manning for an overwhelming majority of ships. In addition to this, legislation on safe manning is very flexible and safe manning levels could be further reduced if technical systems could replace some of the tasks done by human labour today. Unmanned operation may not be legally possible within the existing legal framework and a manning of one person as mentioned in the Danish legislation is perhaps only a theoretical possibility. However, the legislation is not a stopping block for a dramatic reduction of crew sizes for most commercial cargo ships should technical advances make this possible.

6 CONCLUSION

This paper explores the extent to which the existing legislation on safe manning is a bottleneck in the development towards unmanned and/or autonomous operation. Data on safe manning and actual manning sizes of 210 ships is analysed. The results of the analysis of this quantitative data are further qualified by interviews with three representatives from the shipping industry and maritime administration. The study finds that the actual manning exceeds the safe manning on 97% of the analysed ships. 78% of the ships in the analysis have an actual crew size that exceeds the safe manning by 33% or more and on 49% of the ships it exceeds the safe manning by 50% or more. As expected, a strong correlation between ship size and both safe and actual crew size is found. The difference between safe and actual crew size is also found to increase with ship size both in terms of specific and relative numbers. The smallest differences between safe and actual crew size are found in small Ro-Ro passenger ships and the largest differences are found in large containerships.

Based on the interviews, it is found that the shipping companies have a strong competitive and economic incentive to reduce the crew size. Both interviewed companies answer that they could legally reduce their crew sizes within the confines of the safe manning and that they would do so if possible but that the operation and construction of the ships dictate the actual crew sizes. All interviewees see unmanned and/or autonomous operation as being many years off, especially for large commercial cargo ships.

Based on the interviews, it is also found that safe manning is not static and minimum crew sizes could be further reduced if technical systems were proven to be able to safely carry out tasks previously done by human labour. Fully unmanned operation is unlikely to be possible under current legislation. The existing legislation on safe manning, however, does allow for dramatic reductions in crew sizes for the large majority of ships. In general, legislation on safe manning is therefore found not to be a bottleneck in the present state of development of autonomous and unmanned ships.

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Paper VII*

Eriksen, S.; Lützen, M.; Larsen, M.B. **On automation and its potential impact on the workload on merchant ships** *(Submitted 08 July 2021) Maritime Policy and Management*

**Appended as submitted in content but reformated for readable and uniform presentation*

On automation and its potential impact on the workload on merchant ships

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ABSTRACT

This paper explores the automation potential of commercial cargo and passenger ships and its possible impact on the workload required for their operation. Data on the operation and work time distribution from four ships: a Gas tanker; a Ro-Ro; and a large and a small Ro pax, is introduced and analysed. Five work time categories are identified: Navigation; Shipboard operation; Maintenance; Administration; and Catering & hotel service. A model for assessing the automation potential of each work task category based on automation potential indicators is developed and applied. Only Navigation is found to have a high automation potential. Navigation makes up between 12 and 17 per cent of the total work time across the four ships. Shipboard operation is found to have a medium automation potential. This category makes up almost half the work time on the small Ro pax, but only a smaller proportion on the other three ships. The automation potential of the last three categories is found to be low. Overall, the automation potential of the small Ro pax is found to be significant but the potential of the three larger ships is found to be limited.

KEYWORDS

Unmanned ships; Autonomous ships; Automation potential; Workload on ships; Work time categories; Automation potential indicators.

1 INTRODUCTION

Despite being a historically conservative business (Roggema and Smith 1983) shipping has been shaped by the same technological advancements that have transformed our society in general. The first technological revolution came with the introduction of the steam engine towards the end of the 18th century (Schwab 2017). In the 19th century the second industrial revolution brought electrification and telecommunication. The third industrial revolution introduced microprocessors, computerization and digital communication in the second half of the 20th century. All of these technological advances have had dramatic impacts on the maritime world where ships have been growing ever larger at the same time as crew sizes have been getting smaller (MacDonald 2006; Ljung and Lützhöft 2014). In the last two or three decades alone, the typical crew size of an average commercial cargo ship has decreased from 40 or 50 to little more than 20; while container ships, for example, have quintupled in cargo capacity during the same time period

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(Hetherington et al. 2006; Rodrigue 2020). These developments have been driven by the demand for greater efficiency and increased profitability in shipping and have been enabled by advances in engine technology, automation, improved cargo gear, better materials and coatings, etc. (MacDonald 2006). Within the existing technological state of development, however, crew sizes seem to have stagnated at a critical low limit according to Ljung and Lützhöft (2014). Ship crews are overworked, stressed and fatigued, and implementing more of the existing technology appears in many cases only to add to the workload instead of reducing it (Ljung and Lützhöft 2014).

At the turn of the new century the shipping industry finds itself on the brink on what Schwab (2017) has dubbed the fourth industrial revolution. The most direct physical manifestation of this new industrial revolution in the operation of commercial cargo ships is the development of technologies for autonomous vehicles. Even though the idea of autonomous and/or unmanned ships is not new (Bertram 2003), advancements in autonomous road vehicles have urged on a new wave of research and interest in the topic in the maritime world (Jokioinen et al. 2016). Despite the sea being a very different environment to the road, manoeuvring and navigating a ship involves many of the same tasks as driving a car or truck. The driving of a car or the manoeuvring and navigation of a ship is largely a routine task that follows explicit rules, and where the cognitive and manual activities are relatively limited and well defined. Cargo ships are typically much slower than road traffic and there is much more room to manoeuvre at sea, so a ship should, in some ways, be even easier to automate than a car (Jokioinen et al. 2016). There are, however, crucial differences between driving a car and operating large ships, which makes automating the functions of the latter a very different challenge. Cars or trucks are typically operated by one person who is almost entirely engaged in the task of driving. Conventionally manned ships are operated by several crewmembers, typically around 20 for larger ships, of which the manoeuvring and navigation is only part of the work carried out on board during operation (Hetherington et al. 2006).

Large ships are massive structures that dwarf all other forms of transport in both size and cargo capacity, often by orders of magnitude. At the same time, ships are often underway for days or weeks at a time, during which they are practically isolated from external assistance. This requires the capacity and ability of the crew to operate and maintain the ship’s machinery systems. In relative terms, the machinery and service systems of ships may be simple compared to aeroplanes, for example, but because of their size the workload required for their maintenance is considerable. On a conventionally manned ship the majority of this maintenance work is done by the crew during normal operation. Ships today are not as isolated from the home office or the world in general as before but in terms of day-to-day organisation of work tasks, safety drills etc. they are still very much self-governing units. Much of the direct interaction and communication with local authorities, cargo operators, shipping agents, etc. is also still handled by the ship’s crew. Loading and discharging operations of ships typically also rely heavily on the crew. Because the operation of large, conventionally manned ships requires the presence of a permanent crew there must also be facilities and manpower to accommodate and cater for them on board.

Considerable work has been done on the susceptibility of jobs for automation and its impact on the global labour market. Frey and Osborne (2017) conclude that 47 per cent of current jobs in the United States, spanning all sectors but where most are land-based jobs, are at high risk of being replaced by automation. Arntz et al. (2017), however, have challenged this finding and adjust this number down to only 9 per cent. Some work has been done on the impact of automation on the crew size of cargo ships and the future demand for seafarers. Schröder-Hinrichs et al. (2019) conclude, using amongst other things the methods of Frey and Osborne (2017), that automation will be able to reduce crew size by between 16 and 24 per cent by the year 2040. In the analysis, Schröder-Hinrichs et al. (2019) assess the automation potential of specific job profiles based on detailed but generic data. The assessment of the overall impact of automation on the reduction of crew sizes is based on manning assumptions collected through interviews with shipping technology specialists (Schröder-Hinrichs et al. 2019). Kooij and Hekkenberg (2020) analyse the effects of added automation on the required size and composition of the crew of a 750 TEU short sea container vessel. In the study it is assumed that the tasks related to either navigating or mooring the ship are automated. The study finds that, while automating these specific tasks reduces the required workload considerably during some operational phases, the workload in other phases is still high and it may therefore not be feasible to reduce the crew size significantly.

The exploration of issues regarding reductions in crew size and the long-term impact of automation on the global demand for crewmembers is a very important step in understanding the potential effects of autonomous and/or unmanned operation of ships. However, a reduction in crew size is not in itself a direct indicator for reductions in workload and the related labour costs of operating a ship to the extent that job tasks are merely moved from the ship to shore, for example. The number of tasks suitable for automation for each individual job position based on standardised job descriptions, as explored by e.g. Schröder-Hinrichs et al. (2019), is also not an effective proxy for potential reductions in the workload and related costs, for three reasons. Firstly, some tasks may take up significantly more work time than others; secondly, the distribution of tasks and their automation potential vary significantly across job positions and the overall potential therefore depends on the specific crew composition of each ship; and, thirdly, both the crew composition and the distribution and composition of tasks within each job position are likely to vary greatly across different ship types, sizes and operational patterns. So far, no study has been made which quantifies the workload on ships from a work time perspective; which assesses the specific automation potential of the actual categories of work required in the operation of commercial cargo ships; or which includes work time data from across ships of different types, sizes and operational patterns. Hence, this paper will address this issue by: (i) developing and applying a model for assessing the automation potential of the different work categories onboard commercial cargo or passenger ships; (ii) evaluating the potential impact of automation on the overall workload using the results of the model together with data on the work time distribution of four ships of different types, sizes and operational patterns; and (iii) investigate how the different type, size and operational pattern of the four ships affects the automation potential.

The data used for the present analysis and the methodology chosen for the collection of this data is presented in section 2. In section 3, the conceptual model developed for and used in the present analysis is presented. The results and the analysis of the automation potential of the different work categories along with the analysis of the work time distribution of the four ships is presented in section 4, and in section 5 the results and their further implications are discussed.

2 DATA AND DATA COLLECTION

This section presents the data used in the present analysis. Section 2.1 introduces the four vessels from which data was collected and section 2.2 describes the methodology used in the collection of this data.

2.1 THE FOUR SHIPS IN THE ANALYSIS

A short description of the four ships on which the data in the present analysis was captured is presented here. The four ships are a Ro-Ro ship, a Gas tanker and a small and a large Ro pax. These four ships represent vessels of different sizes, types and operational patterns. General information on the four ships in the analysis can be seen in Table 1.

Table 1 Table 1 Particulars of the four ships in the analysis

Ship type	Length [m]	Gross register tonnage [GRT]	Voyage length	Typical time for cargo operation	Engine effect [kW]	Crew size* (actual)	Crew size (min. safe manning)
Ro-Ro	195	33313	18.5 hours	5.5 hours	18160	17	11
Gas Tanker	115	7465	NA†	12-24 hours	5920	15	11
Ro pax (small)	50	1617	75 min.	15-20 min	2040	5 - 8‡	5 - 7‡
Ro pax (large)	142	14820	45 min.	15-20 min	16673	16 - 52‡	11 - 20‡

**Value at the day of data sampling. Actual crew size can change over time.*
†Vessel is in tramp trade and voyage length therefore varies greatly.
‡Both actual and minimum safe manning vary depending on passenger capacity and change throughout the day.

Operational pattern

The Ro-Ro and the two Ro pax vessels are operating fixed routes between two ports while the Gas tanker is in tramp trade. The small Ro pax is operating between about 0600-2400, depending on the sailing schedule, and is stationary in port at night. The other three ships are in continuous 24-hour operation.

Crew

Crews of the Ro-Ro and Gas tanker are mustered onboard for weeks or months at a time depending on the contract. The small Ro pax does not have permanent accommodation for the crew, who will board and disembark the ship at the start and end of each shift. On the large Ro pax the working arrangement is a mix of the two options. Some of the crew are mustered onboard for three or four days at a time and others are only onboard during work hours.

Cargo operation

Both Ro pax ferries transport vehicles of all kinds, as well as passengers. Vehicles are guided onto the car deck by the crew but are, with few exceptions, operated by their individual drivers.

The Ro-Ro ship transports primarily unaccompanied cargo trailers, but also other rolling cargo, which is driven on and off the ship by stevedores. On the Ro-Ro the crew is also responsible for the positioning of the cargo and, because the voyage is longer and the vessel crosses the open sea, also for securing the cargo.

The gas tanker transports refrigerated and pressurized liquified gas in bulk. During loading and discharging the ship is connected to the shore terminal via the ship's cargo manifold and the liquified gas is pumped on or off the ship in a sealed pipe system. All onboard cargo operation is handled by the crew and is closely coordinated with the shore side.

2.2 Field work, interviews and observations

The main source of data used in the present analysis is the details and distribution of the work time of the crew, collected through interviews and observations. This is supplemented by documentary data including ship's logbooks, crew work plans and rest hour reporting, crew lists, crew job descriptions, and sailing schedules. The interviews and observations, along with the majority of the documentary data, were collected by the authors for use in this analysis during field studies onboard the four vessels described in section 2.1. The first field study was performed on the Gas tanker in June 2019 and the last field study was conducted on the small Ro pax in January 2021. The field studies were carried out onboard while the ships were in active operation. On the two Ro pax the data was gathered during transit, and, on the Ro-Ro, it was gathered during a normal port operation. The field study on the Gas tanker was more involved, as it took place over the course of ten days when the ship was in normal operation at anchor, manoeuvring, loading and during sea passage. All senior officers were interviewed, along with as many other crewmembers as the time allowed. The work task description and time distribution of some junior officers and ratings, however, were reported by their immediate work leader or colleague who had comprehensive knowledge of the specific job functions.

Although qualitative in nature the observations and interviews focused mostly on the quantitative aspects of which onboard work tasks the operation of the ship involves and how the work time is distributed between the different work tasks. The interviews were primarily structured but also contained questions of a qualitative nature regarding the suitability of, potential for and barriers to different tasks for automation that followed a more semi-structured approach. Self-reporting on the distribution of work tasks through interviews, such as that used for the present analysis, has its limitations with regard to how accurately respondents are able to judge the length of time they spend on each task. However, the uncertainties of self-reporting are well understood, and the method is used extensively in a wide variety of research fields (Hartley et al. 1977).

3 Conceptual Model

This section presents the conceptual model used for the evaluation of the automation potential of the work time categories in the present study. The evaluation of the extent to which work tasks currently being done on commercial cargo ships are suited for automation is based on the positive or negative indicator presented in section 3.1. Section 3.2 introduces the automation potential model in which the identified indicators are used.

3.1 Automation potential indicators

According to Acemoglu and Autor (2011), automation is best suited for routine tasks characterised by being a limited and well-defined set of cognitive and manual activities, and which can be accomplished by following explicit rules. Automation can, according to Acemoglu and Autor (2011), complement but not replace human labour in non-routine tasks that require problem solving and complex communication activities. Non-routine tasks can generally be divided into two major categories, which are found at both ends of the occupational skill spectrum: namely, abstract tasks and manual tasks. Abstract tasks require problem-solving, intuition, persuasion and creativity. Manual tasks require situational adaptability, visual and language recognition and in-person interactions. The findings of Frey and Osborne (2017) follow along the same general lines. They identify three main bottlenecks in the computerisation of jobs: perception and manipulation; creative intelligence; and social intelligence. These three bottlenecks involve aspects such as social perceptiveness, negotiation, persuasion, working in cramped spaces or awkward positions and manual and finger dexterity. Others such as Billard and Kragic (2019) and Kemp et al. (2007) also emphasise dexterous manipulation as an area where robots/automation significantly lag behind human capabilities.

The theory presented here forms the basis of the automation potential indicators used in the present analysis as presented in Table 2. Some common characteristics identified in the theory have been summarised into single indicators. The ‘Social intelligence’ indicator also encompasses in-person interactions, for example.

Table 2 Automation potential indicators

Positive automation indicators:	**Negative automation indicators:**
• Routine tasks • Limited and well defined cognitive and manual activities • Can be accomplished by following explicit rules	• Non-routine tasks • Tasks which require: – Problem solving – Situational adaptability – Complex communication activities – Intuition – Persuasion/negotiation – Social intelligence – Manual and finger dexterity – Working in cramped spaces

That there are more negative than positive indicators is only an expression of the level of detail of the former, not an indication of an overall automation potential.

3.2 AUTOMATION POTENTIAL MODEL

The conceptual automation potential model used in the present analysis is shown in Figure 1. Data from the field work described in section 2.2 is used to define the work time categories and to determine the work time distribution. Each work time category is evaluated using the automation potential indicators described in section 3.1 and the automation potential of each category in presented in section 4.1. The work time distribution is introduced and the potential impact of automation on the overall workload is presented in section 4.2

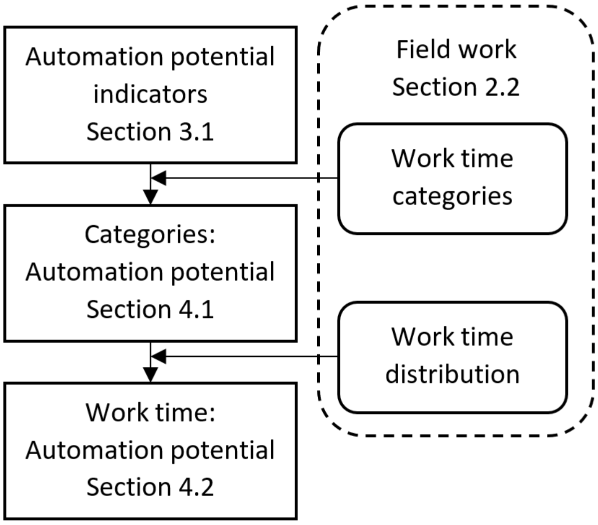

Figure 1 Automation potential model

4 RESULTS AND ANALYSIS

In this section the analysis and the results of the analysis of the data described in section 2 are presented. Section 4.1 presents the work time categories and the automation potential of these. In section 4.2 the analysis of the total work time distribution and the overall automation potential for the four ships is presented.

4.1 WORK TIME CATEGORIES AND AUTOMATION POTENTIAL

As described in section 1, the work involved in the operation of a commercial cargo ship is considerable. It extends beyond the task of manoeuvring and navigating the ship, and not all the work has the same potential for automation. Based on observations and interviews with the crew members during the field study, as described in section 2.2, the following five work time categories are defined: 'Navigation', 'Shipboard operation', Maintenance', 'Administration' and 'Catering & hotel service'. The categories are also seen in Table 3.

The categories are relatively broad to be able to encompass the work of all crew members and the very different operational patterns of the four ships in the present analysis. The categories follow lines of comparable work tasks but also to some extent follow the traditional departments onboard. 'Catering & hotel service' only involves the work of the catering department, for example, whereas all crew members have tasks in the 'Administration' category. The work tasks presented in Table 3 are representative of the work done in each individual work time category and include tasks that span across all four ships. However, the list of work tasks in Table 3 is not exhaustive.

Based on information of work tasks from the field work, positive and negative automation indicators as described in section 3.1 are now assigned to each work time category. Because of the variability of tasks within each category, both positive and negative automation indicators can be simultaneously assigned to the same category. A category may, for example, contain both routine and non-routine tasks. Finally, each category is assigned an automation potential of either high, medium or low based on an overall qualitative assessment of the automation indicators.

Table 3 Automation potential for the five work time categories

Work time category	Work tasks*	Positive automation indicators	Negative automation indicators	Automation potential
Navigation	– Monitoring and control of ship's movements – Lookout – Anti-collision planning and execution – Radio communication – Passage planning – Operating instruments	– Routine tasks – Limited and well-defined cognitive and manual activities – Can be accomplished by following explicit rules	– Situational adaptability – Complex communication activities – Intuition – Persuasion/negotiation	High
Shipboard operation	– Monitoring and operating instruments and machinery – Loading and discharging of cargo – Bunkering and transfer of fuel oil, other consumables and ballast – Mooring and establishing cargo connection to shore – ISPS watch	– Routine tasks – Can be accomplished by following explicit rules	– Non-routine tasks – Problem solving – Situational adaptability – Complex communication activities – Intuition – Social intelligence	Medium
Maintenance	– Disassembly, assembly and repair of machinery and structures – Inspections, functional testing and measurements – Diagnostic – Troubleshooting – Fabrication of non-standardised parts	– Routine tasks	– Non-routine tasks – Problem solving – Situational adaptability – Intuition – Manual and finger dexterity – Working in cramped spaces	Low

Administration	– Daily personnel management – Communication – Documentation – Requisitions – Work time planning and rest hour management – Safety and planning meetings	– Routine tasks	– Non-routine tasks – Complex communication activities – Intuition – Persuasion/negotiation – Social intelligence	Low
Catering & hotel service	– Cooking and serving – Storekeeping and requisitions – Cleaning, making beds, washing linens, towels, etc.	– Routine tasks	– Non-routine tasks – Social intelligence – Manual and finger dexterity	Low

*Tasks done across all ship types in the present analysis. The list is not exhaustive

As seen in Table 3, 'Navigation' is the only category assessed to have a high automation potential. Many 'Navigation' tasks are routine tasks and can to a large extent be accomplished by following explicit rules. The tasks in the 'Navigation' category are also very similar across most ship types and operating patterns. However, automating the 'Navigation' tasks is by no means straightforward. The rules of the maritime collision regulations (COLREG) are not totally explicit and leave considerable room for interpretation (Porathe 2017). 'Navigation' still requires situational adaptability, complex communication activities, intuition, persuasion and negotiation. There are also still unsolved challenges relating to computer object detection and recognition (Barkhordari et al. 2021).

Many of the tasks in the 'Shipboard operation' category are similar in nature to those in 'Navigation' in that they revolve around what can be described as operating the ship. Many tasks involve monitoring and controlling the operation of machinery or tank levels, flow rates, temperatures or other physical parameters that can be accomplished by following explicit rules. 'Shipboard operation', however, consists of a large variety of smaller separate tasks that differ greatly across ship types and operational patterns. Many tasks, such as loading and discharging, typically also involve interaction with shore systems and workers, which requires social intelligence and complex communication activities. The operational boundaries for each task can also vary greatly from one time to the next, requiring problem solving, intuition and situational adaptability. Some tasks within the category will be possible to automate and others will not. The overall automation potential of the 'Shipboard operation' category is considered to be medium.

The 'Maintenance', ' Administration' and 'Catering & Hotel service' categories all contain some tasks which can be said to be routine within the framework of Frey and Osborne (2017). However, the negative automation potential indicators are much more prominent over the three categories as a whole and their automation potential is therefore assessed to be low. 'Maintenance' involves a lot of problem-solving, intuition and situational adaptability, besides working in cramped spaces. Both 'Maintenance' and 'Catering & hotel service' rely heavily on manual and finger dexterity. Social intelligence plays an important role in both 'Catering & hotel service' and 'Administration'. Because 'Administration' involves personnel management and communication it also involves persuasion, negotiation, intuition and complex communication activities. Overall, these three categories are extremely poor candidates for automation.

4.2 WORK TIME DISTRIBUTION

Figure 2 shows the distribution of the work time in the five categories for the four ships. The two cargo ships, the Gas tanker and the Ro-Ro, show remarkably similar work time distributions, despite having very different operational patterns, as described in section 2.1. For both these ships, 'Maintenance' is by far the largest category and accounts for more of the workload than 'Shipboard operation' and 'Navigation', the next biggest categories, combined.

Except for 'Navigation', the two Ro pax are very different, not only from the cargo ships and but also from each other, despite the two having very similar operational patterns. 'Maintenance' still makes up a large portion of the work time on the large Ro pax, but only seven per cent on the small one. 'Shipboard operation' takes up almost half the work time on the small Ro pax, more than double the proportion of time than any of the other ships, and more than six times that of the large Ro pax.

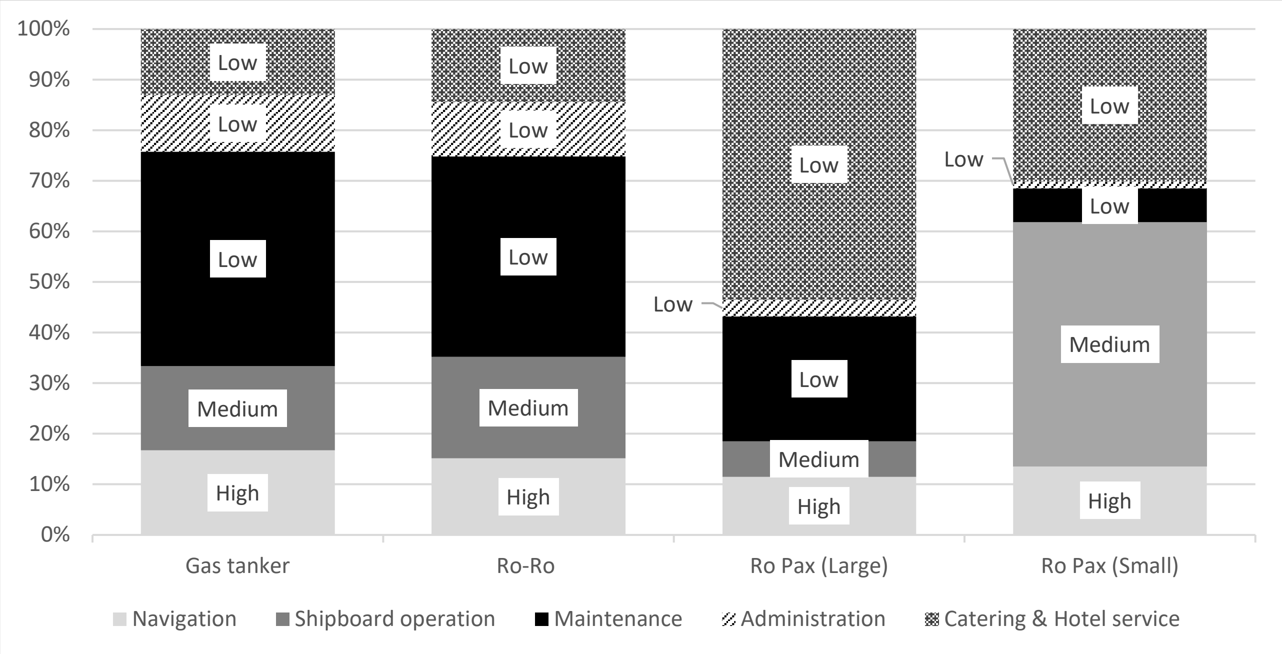

Figure 2 Distribution of work across analysed vessels, automation potential indicated

On both the Ro pax, the catering and hotel department primarily services the passengers, and the proportion of work used in this category is, as expected, large. On the large Ro pax, more than half the time is used on 'Catering & hotel service'. Because this category is so large on both the Ro pax – and because the tasks involved in this category are so different between passenger and cargo ships – it is hard to assess the relative sizes of the remaining work time. To better compare the other work time categories the work time distribution is plotted without 'Catering & hotel service' in Figure 3.

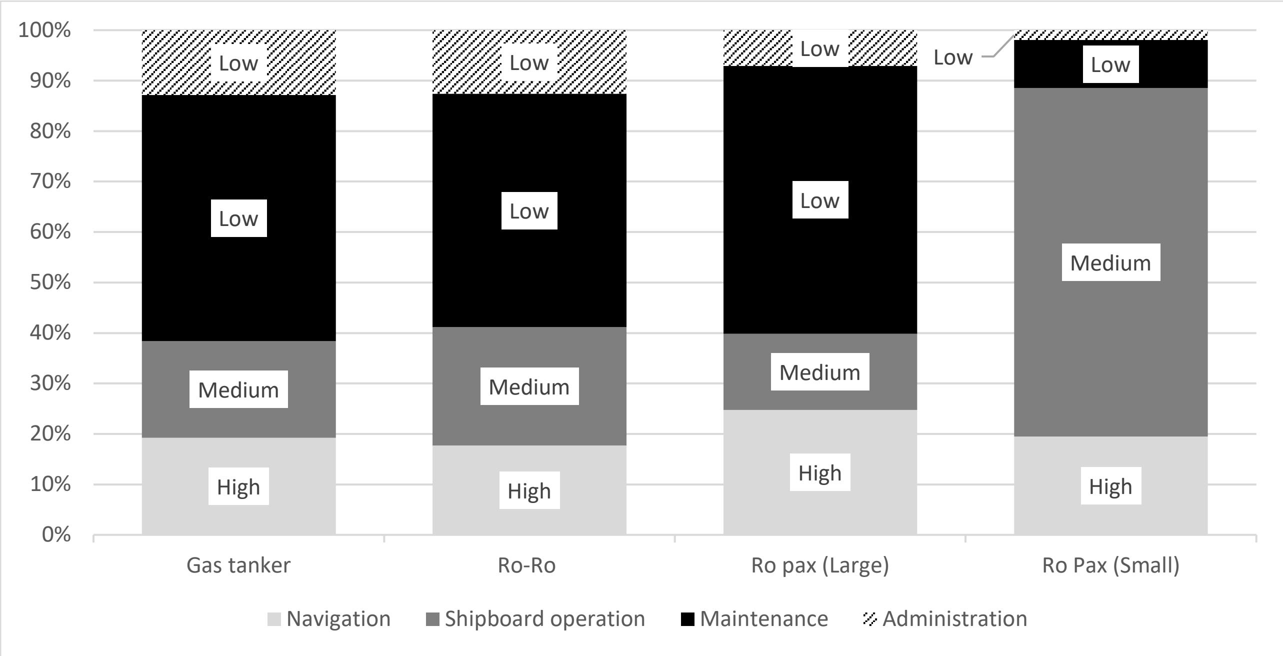

Figure 3 Distribution of work across analysed vessels, Catering & hotel service not included, automation potential indicated

Plotted in this way the work time distribution of the large Ro pax is remarkably similar to that of the two cargo ships, despite having fundamentally different operational patterns. 'Maintenance' makes up more than half the remaining work time on the large Ro pax, even exceeding that of the cargo ships. The small Ro pax really stands out from the three other ships, with only 10 per cent of the work time spent on 'Maintenance' and almost 70 per cent spent on 'Shipboard operation'.

'Navigation' is strikingly similar across all four ships, making up between 18 and 25 per cent when 'Catering & hotel service' is excluded. 'Shipboard operation', which has a medium potential for automation, is also quite similar on the Ro-Ro, Gas tanker and large Ro pax at between 15 and 23 per cent. The combined proportion of work with high or medium potential for automation is almost precisely 40 per cent on these three ships. For the remaining 60 per cent of work tasks, the potential for automation is therefore low, even when 'Catering & hotel service' is not considered.

The small Ro pax distinguishes itself from the other three ships in the present analysis by the large amount of work time that has potential for automation. The proportion of work relating to 'Navigation', which has a high potential for automation is, perhaps surprisingly, not higher for the small Ro pax than for any of the other ships. 'Shipboard operation' as described in this section, however, which has a medium potential for automation, makes up almost 70 per cent of the work on the small Ro pax. Only 12 per cent of the work on the small Ro pax has a low potential for automation. The reason for the similarities and differences in the automation potential and the opportunities and challenges related to automating work tasks on commercial cargo ships in general is further discussed in section 5.

5 Discussion

The results and the analysis of the present study shows that there are great differences in the automation potential across the five work time categories. Where much of the human labour related to 'Navigation' can potentially be automated, the workload related to other categories will not be similarly affected. The potential impact of automation on the overall workload thus depends entirely on the distribution of the work time on each specific ship. There are both great similarities and great differences in the work time distribution, and thus the overall automation potential, of the four different ships in the analysis.

Despite differences between the four ships in e.g. length by a factor of four, in crew size by a factor of ten and in GRT by a factor of more than twenty, the proportion of time spent on 'Navigation' only varies between 12 and 17 per cent. Neither size, type nor operational pattern clearly have any great impact on this work time category. The Gas tanker and the Ro-Ro are very similar across all categories, suggesting that cargo ships are largely comparable in terms of work distribution, despite central differences in design, cargo type and operational pattern. The mode of operation ties the two Ro pax together in the sense that 'Catering & hotel service' makes up a significant part of the workload. When 'Catering & hotel service' is removed from the total workload, however, the similarity between the two Ro pax ceases and the work time distribution of the large Ro pax closely resembles that of the two cargo ships. Without 'Catering & hotel service', 'Maintenance' becomes the dominant work time category on the three large ships, making up almost half of the work time. The size of the ships clearly has a strong influence on the work time distribution. Findings on the impact of automation on the workload, and by extension on labour costs, from studies of one size of ship therefore cannot be transferred directly to ships of different sizes. Precluding the 'Catering & hotel service' category, the operational pattern and the type of large ships does not appear to have a large influence on the work time distribution. Despite fundamental differences in trade patterns, construction and cargo handling, the work time distribution of the Gas tanker, the Ro-Ro and the large Ro pax is within a few percentage points of each other across all the remaining work time categories.

The findings in the present paper are based on a significant amount of data collected through extensive field work on four ships in operation. There are, however, some limitations and uncertainties that must be considered. Only onboard work is included in the analysis, but the operation of cargo ships involves the work of numerous different external actors, such as the shipping company shore organisation, classification societies, service contractors, etc. Quantifying the work of all external actors related to an individual ship, however, would neither be feasible nor useful for the present analysis. It is also important to note that the work time distribution is a snapshot of the normal operation of the four ships at the time of data sampling. This distribution may vary over time depending on season, age of the ship, trade pattern, etc. The properties of the four ships used in the present analysis and their operation are characteristic of a large group of cargo and passenger ships in operation today but they by no means represent all cargo ships. The findings in the present paper are illustrative of the nature of the workload on merchant ships in general, but the specific work time distribution values presented here should not be extrapolated directly to specific ships outside the analysis.

In section 4.1 the potential for automation is divided into three levels: high, medium or low. Translating these levels into exact reductions in the workload is very difficult. A high potential does not mean that the workload can be fully eliminated. Automated navigation is proposed to be supplemented with remote monitoring, for example, and the ships are assumed to be periodically manned or remote-controlled in high-density traffic situations or during arrival or departure (Porathe et al. 2013; Kretschmann et al. 2015; Jokioinen et al. 2016). However, if 'Navigation' can be automated, even periodically, and the navigation bridge does not have to be continuously manned, it will potentially have a significant impact on the workload in this category. A low potential also does not mean that automation cannot reduce the workload of any tasks. A few tasks in the 'Maintenance' category, such as functional testing, for example, could conceivably be automated. In general, however, the impact of automation on the workload can be expected to be negligible for the categories with a low automation potential. In between the two extremes lies ‘Shipboard operation’ with a medium automation potential. Because the work tasks included in ‘Shipboard operation’ are so dependent on the specific operation and construction of the ship, the exact automation potential is also likely to vary greatly across the four ships. Automation solutions developed for work tasks in this category for one type of ship or operation cannot necessarily be used on other ships. All reservations aside, the overall automation potential and potential reduction in workload looking broadly across all the ship types is probably in the same size range as the 16 to 24 per cent reduction in crew size as concluded by Schröder-Hinrichs et al. (2019).

In the discussion of the automation potential of ships it is important to remember that modern cargo ships are already highly automated and are already operating with a greatly reduced crew compared to just a few decades ago (Hetherington et al. 2006). With this in mind, it is perhaps not surprising that the automation potential identified in the present analysis is not greater than it is. On the other hand, the fact that there still is automation potential indicates that ships are not designed purely to maximize automation and reduce human labour. Barring the systems needed for unmanned ‘Navigation’, which are not yet commercially mature, existing technologies could probably fulfil much of the identified automation potential. That a work task has the potential to be automated, however, does not mean that it will be. Aside from regulatory barriers (Van Hooydonk 2014; Carey 2017; Danish Maritime Authority 2017) the implementation of automation also needs to be economically feasible (Schröder-Hinrichs et al. 2019). This issue is aggravated by the heterogeneous nature of the workload across the different modes of operation of the ships, as pointed out by Kooij and Hekkenberg (2020), among others. Port operations, for example, are a work intensive mode of operation and require the participation of the whole crew. Transferring the loading and discharging workload to a shore crew may not be practically possible or economically feasible (Kooij and Hekkenberg 2020). Automating job tasks in one category such as ‘Navigation’ may be technically possible, but the economic incentive may be limited if the crew size cannot be reduced because of bottlenecks in other categories.

The analysis in the present paper focuses on the reduction in the workload as an indirect measure of the potential of automation in reducing the cost of operating commercial cargo ships. There may be secondary reasons to pursue reductions in crew size, such as safety or difficulties related to crew changes as highlighted by the COVID-19 pandemic. There is little doubt, however, that the main interest in smaller crews is a reduction in crew costs (MacDonald 2006; Eriksen 2019). Developments within autonomous and/or unmanned operation of ships have so far been mostly focused on automating the task of driving the ship (Kooij and Hekkenberg 2020; Rødseth and Vagia 2020). Because ‘Navigation’ only makes up a comparatively small part of the workload, however, driving automation in itself will have a relatively limited impact on all four ships. When the perspective is widened and the automation of tasks in the ‘Shipboard operation’ category is considered, the automation potential for the small Ro pax becomes significant. For large cargo and passenger ships, as represented by the other three ships in the analysis, the automation potential is still low for the majority of the work tasks despite the inclusion of ‘Shipboard operation’.

6 CONCLUSION

This paper explores the automation potential of commercial cargo ships and its possible impact on the workload required in operating these ships. The analysis is based on data collected through field work on four ships: a Gas tanker; a Ro-Ro cargo ship; and a large and a small Ro pax. Data on which work tasks the operation of these four ships require and on how the work time is distributed between these tasks is introduced and analysed. Five work time categories are developed based on this data and a model for assessing the automation potential of these categories is developed and applied. The work related to the 'Navigation' category is evaluated to have high automation potential; work in the 'Shipboard operation' to have medium potential; and the three categories 'Maintenance', 'Administration', and 'Catering & hotel service' to have low automation potential.

The proportion of work with high potential for automation, that which relates to 'Navigation', is very similar between the four ships at between 12 and 17 per cent of the total workload. On the two cargo ships, the Gas tanker and the Ro-Ro, the distribution of work is very similar across all the five categories, despite large differences in the operational patterns. 'Maintenance' is the largest category, making up around 40 per cent of the total workload. The two Ro pax are similar in that a large part of the total workload is used on 'Catering & hotel service'. When this category is excluded, however, the work distribution of the remaining categories on the large Ro pax resembles that of the two cargo ships rather than the small Ro pax, suggesting that ship size has a large impact on the distribution of work tasks. The small Ro pax stands out from the other three ships in that almost half the workload is used on 'Shipboard operation', compared to 17-20 per cent on the cargo ships and only 7 per cent on the large Ro pax.

The study finds that the overall workload cannot be significantly reduced if the focus is solely on automating tasks related to 'Navigation'. When the automation of 'Shipboard operation' is considered, a significant part of the work on the small Ro pax has the potential for automation but the automation potential for the majority of work tasks on the other three ships is still low. The fact that a task or category has the potential for automation does not mean that it is practical or economically feasible to do so. The automation potential therefore does not translate directly into reductions in workload and related costs. Overall, however, the study finds that, while automation has a significant potential impact on the workload of small Ro pax ferries, the automation potential on larger cargo or passenger ships is limited.

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DECLARATION OF INTEREST STATEMENT

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

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Co-author statements

Co-author Statement

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The undersigned who is: ☐ corresponding author ☒ co-author on the paper/manuscript above, hereby confirms that (name of the PhD student) Stig Eriksen has contributed to the work as stated below:
1. Intellectual input: ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:
2. Experimental results (indicate contribution to individual figures, tables and supplementary data): ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:

3. Writing process:

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The undersigned who is: ☐ corresponding author ☒ co-author on the paper/manuscript above, hereby confirms that (name of the PhD student) Stig Eriksen has contributed to the work as stated below:
1. Intellectual input: ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:
2. Experimental results (indicate contribution to individual figures, tables and supplementary data): ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:

3. Writing process:

☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100%

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Concerning the paper/manuscript:
Authors, title, journal: Eriksen, S. Lützen, M. The impact of redundancy on reliability in machinery systems on unmanned ships, submitted to WMU Journal of Maritime Affairs
The undersigned who is: ☐ corresponding author ☒ co-author on the paper/manuscript above, hereby confirms that (name of the PhD student) Stig Eriksen has contributed to the work as stated below:
1. Intellectual input: ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:
2. Experimental results (indicate contribution to individual figures, tables and supplementary data): ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:

3. Writing process: ☐ less than 25% ☐ 25 - 50 % ☐ 50 - 75% ☒ 75 - 100% Comments:
Name of co-author (capital letters): Marie Lützen
Signature of co-author and date: 4/8-2021 Marie Lützen

Manuscripts of previously published articles may be included in the PhD thesis. If articles included in the PhD thesis have been written in cooperation with others, a co-author statement from each of the authors must be attached stating the extent of the PhD student's contribution to the total work.

Co-author Statement

Co-author statement in connection to the PhD thesis made by:
Name of PhD student: Stig Eriksen
Concerning the paper/manuscript:
Authors, title, journal: Eriksen, S. Lützen, M. The impact of unmanned operation of ships on the maintenance work burden and related costs, submitted to WMU Journal of Maritime Affairs
The undersigned who is: ☐ corresponding author ☒ co-author on the paper/manuscript above, hereby confirms that (name of the PhD student) Stig Eriksen has contributed to the work as stated below:
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Name of PhD student: Stig Eriksen
Concerning the paper/manuscript:
Authors, title, journal: Eriksen, S. Lützen, M. Manning the unmanned ship: Is safe manning legislation a bottleneck in the development of autonomous ships? Submitted to SN Social Sciences
The undersigned who is: ☐ corresponding author ☒ co-author on the paper/manuscript above, hereby confirms that (name of the PhD student) Stig Eriksen has contributed to the work as stated below:
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Co-author Statement

Co-author statement in connection to the PhD thesis made by:
Name of PhD student: Stig Eriksen
Concerning the paper/manuscript:
Authors, title, journal: Eriksen, S. Lützen, M. Larsen, M.B. On automation and its potential impact on the workload on merchant ships, submitted to Maritime Policy and Management
The undersigned who is: ☐ corresponding author ☒ co-author on the paper/manuscript above, hereby confirms that (name of the PhD student) Stig Eriksen has contributed to the work as stated below:
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