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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

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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 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 near here]**

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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