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Statistical Reliability Analysis of Marine Systems with varied Levels of Redundancy

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ABSTRACT

In designing autonomous vessels for long-duration independent operation, maintaining the performance of machinery systems without human intervention is a key challenge. Designers are faced with a range of potential system architecture choices but have little guidance on which will be optimal. Working only with high-reliability components can increase the probability of completing a voyage successfully, though the availability of such components may be limited. Alternatively, designers can select a redundant architecture to provide options for reconfiguration if a component fails during a voyage, such architectures typically have weight, space, and cost implications. This work presents a parametric exploration of the probability of system failures over time under different architectures. The reliability of individual components is expressed through exponential probability distributions and the weight of each component is approximated. Two systems are presented and the effectiveness of various architectures for both systems is compared. A simple design penalty function is also tracked to capture the different architectures' weight and implication number of components. From this study optimal architectures for long-term autonomous missions are proposed.

KEY WORDS

Reliability; Redundancy; Series-Parallel Configuration; Marine Systems; Fuel Oil System; Cooling System.

INTRODUCTION

Ship systems are highly sophisticated systems, being comprised of many subsystems and numerous components. Components in these systems are often placed in parallel configuration on-board ships as a safeguard against catastrophic system failures. Ensuring spare parts are on-board and readily available during emergency is vital to performance of the ship and the ensured safety of the crew. This point is reinforced by classification societies, such as American Bureau of Shipping (ABS, 2018), Lloyds Register of Shipping (Lloyds Registrar of Shipping, 2013) and also International Marine Organization (IMO, 2002), which all have established guidelines for redundancy levels in critical systems, such as main propulsion. Guidelines on system redundancy exist for both main engine systems and their supporting systems, such as engine cooling water, fuel oil, and lube oil systems (Liberacki, 2007). Generally, societies require systems to have secondary pumps and valves in major systems because these parts are known to have high rates of failure. While parallel configuration of components may mitigate system failures, the precise balance required for optimal operation and reliability over a desired period remains ambiguous, prompting the need for a more data driven approach. This approach toward including reliability in systems has not proven to prevent critical failures of systems or unexpected maintenance being necessary. The existing redundancy rules also assume humans are on-board the vessel, which means the systems must be reliable and safe enough to mitigate risk to human life. Assuming a crewed vessel also implies that there will be human intervention if a system malfunction or failure is found by the crew, happening in the form of maintenance, reduction in the operating state of the vessel, or a return to port. For a crewless vessel however, their may be a higher risk profile that is acceptable since there are no human lives at stake.

As the maritime industry progresses toward autonomous operations, reliance on human intervention for system monitoring diminishes, deepening the importance of accurate predictive maintenance strategies. Traditional methods such as scheduled inspection and condition-based monitoring will become more heavily influenced by the predictive models that leverage component reliability data for failure predictions. Accuracy of such predictions requires historical data, which is scarce in the maritime sector due to limited sharing of failure statistics. Data sharing in this industry is driven by mutual benefit, often

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resulting in retention of vessel and component data deeming it to be confidential (Teijl, 2014). Despite this, recent reports can be found which utilize confidential data and present their limited findings (Knežević et al., 2022). Additional information may be gathered from reports which interview crew members and vessel maintenance workers, many of which mention that preventative maintenance and avoiding machinery failures are a major concern in mission planning (Sulkowski et al., 2022). Reports such as these can be leveraged in statistical investigations and predictive modelling approaches such as the one presented here.

Current redundancy standards lack statistical foundation proving the level of redundancy can lead to overall improvements in system reliability. Predictive modelling approaches also lack consideration concerning factors such as component weight and cost. Addressing this gap, this work aims to quantify the trade-offs between high-reliability components and redundancy through simulations, assessing various configurations for their redundancy levels, reliability, and weight. The systems that have been analyzed include the engine cooling water and fuel oil systems. Results from the study conducted here may offer insights into optimal system configurations and informing future standards in naval system design practices.

First, the metrics defining system reliability are presented. Next, assumptions made to estimate weights of components are detailed. An overview of the initial models for both systems is given and the results of testing various configurations of these systems with differing levels of redundancy are presented. Finally, conclusions are drawn from observed trends.

MODELLING ASSUMPTIONS

Reliability Metrics

Reliability of a component has long been defined as “the probability that a component will be able to perform a required function for a given operational period and stated conditions” (MIL-STD-721C, 1981). Various metrics have been used to quantify a components reliability. The chosen metrics for analysis in this paper are average failure rate and mean time between failures for each component tested. A component or systems rate of failure (Equation [1]) and mean time between failures (Equation [2]) are defined as:

$$Failure\ Rate\ (\lambda) = \frac{total\ number\ of\ failures}{operational\ time} \qquad [1]$$

$$Mean\ Time\ Between\ Failure\ (MTBF) = \frac{operational\ time}{\lambda} = t_f - t_0 \qquad [2]$$

These definitions assume a fixed operational time. Failure rate is given in units of failures per million operating hours, so a operational time of 1 million hours has been assumed. Mean time between failures may also be defined in terms of a difference between the time related to a component’s maximum reliability, the initial operation start time, t_0, and the components time of failure, t_f. This modelling approach will assume no maintenance interventions or environmental affects. All components are modelled individually with distinct average lifetimes and average rates of failure. The python *SciPy* package was utilized for creating exponential random variate distributions of failure times for each component. From each distribution 1000 random failure times were selected.

Reliability metrics for this study were taken from multiple sources with all components designated supporting an approximately 17,000kW 6-cylinder Diesel Engine (MAN, 2009). For the high-pressure pumps, metrics come from a study investigating the optimal maintenance plan for high pressure fuel systems (Knežević et al., 2022). Metrics for the low-pressure pumps, heat exchanger, and cross tie valves are sourced from a study optimizing maintenance of heat exchange systems for submersibles (Zhang, 2021). SciPy random exponential function is defined by a variance of failure and not a failure rate, therefore the variance of failure is set so that each parts exhibits the failure pattern described by the failure rates gathered.

Table 1: Reliability Metrics for Components Considered

Component	Mean Time Between Failure (MTBF) (Years)	Variance of Failure Used in Simulation (Years)	Failure Rate (λ) (fails/10^6 Hrs.)
Low-Pressure Pumps	1.97	0.30	56.88
High-Pressure Pumps	0.54	0.08	208.69
Heat Exchangers	6.85	1.65	16.36
Valves	27.52	4.48	4.07

SYSTEM MODELS

Two marine propulsion support systems are included in this paper: the fuel oil system and the cooling water system. A failure of either system can lead to malfunction or failure of propulsion systems which would be a critical failure. Both system configurations are based initially on the schematics of the Marine Design Laboratory, a propulsion simulator at the University of Michigan which emulates shipboard machinery systems using six coupled systems (Marine Engineering Laboratory, 2022). Of the existing ship systems in the simulator, the cooling and fuel oil systems feature redundancy of cooling lines and fuel injection lines, as well as simulation valves for clogs and leaks. In this paper, the initial system configurations only included in-series layout of components with high rates of failure, such as pumps, valves, and heat exchangers will be considered. Clogs and leak simulator valves were removed and other components of the systems with lower rates of failure were also ignored. Additionally excluded components include oil service tanks and cooling water tanks as they are not prone to failure and are low risks components of these systems.

Engine Cooling System

The cooling water system consists of 6 total components, which were divided into two groups. The first group consisted of a single cooling pump and three valves, valve #1, #2, and valve #3 respectively. The cooling pump was considered as a centrifugal pump, assuming the reliability and weight of a low-pressure pump. The second group consisted of a heat exchanger and a final valve, valve #4. Components were considered in two groups so that parallel lines for cooling pumps or parallel heat exchangers could be implemented in testing various configurations. The initial layout of the cooling system is seen below with the component of highest failure rate highlighted in red in Figure 1. In this initial configuration, it was determined that the low-pressure cooling water pump causes cooling system failure most often.

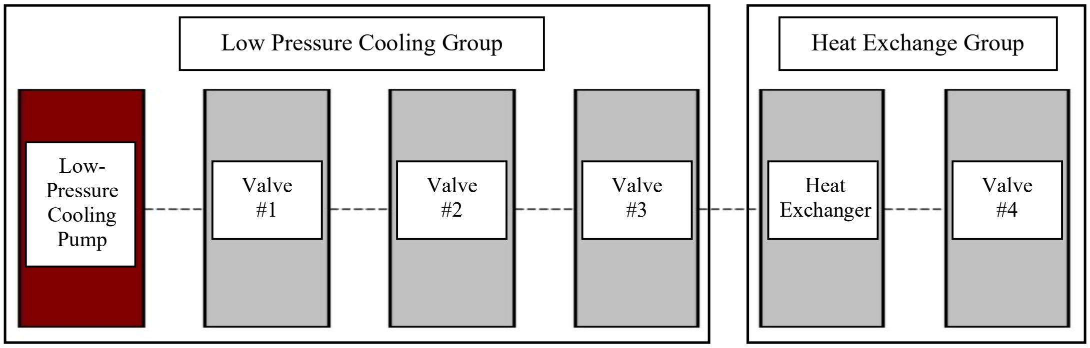

Figure 1: Initial Engine Cooling System Model

For this initial system layout, a reliability over time curve was generated as seen below, over a period of 100,000 operating hours. The system reliability followed the lowest reliability of all parts in the system at each time step, which happened to be the low-pressure cooling pump at all times tested. The four valves have similar reliability curves to each other as expected and showed slightly higher reliability at each time step compared to the cooling pump. The reliability of the heat exchanger far exceeds the reliability of the low-pressure cooling pump and valves. Due to this observation, most tested configurations of this system will investigate adding cooling pump groups in parallel, rather than parallel heat exchange groups in order to improve overall system reliability.

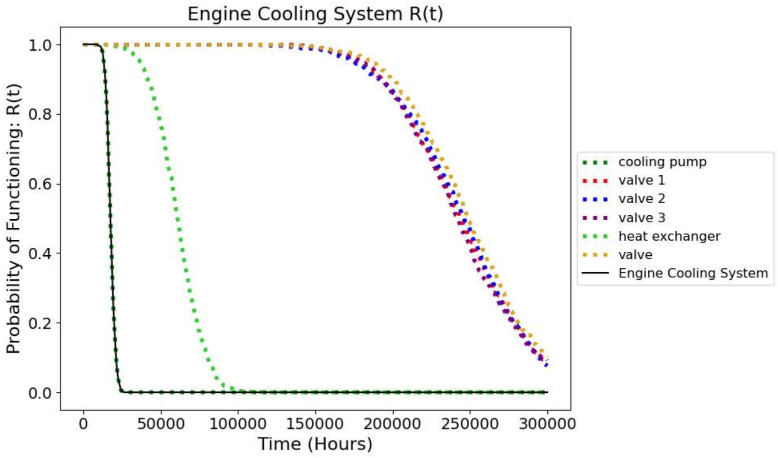

Figure 2: Initial Engine Cooling R(t), Reliability over 100,000 operating Hours

Fuel System

The fuel oil system consisted of 7 components total. These components were again split into two distinct groups. Starting with the cooling pump, valve #1 and valve #2 they were referred to as the fuel cooling group. The fuel injection group was comprised of a high-pressure fuel injection pump and valves #3, #4, and #5. This grouping allows for investigation of parallel lines of fuel cooling or fuel injection during testing. For this system, the fuel injection pump was the component with the highest failure rate, highlighted in red in Figure 3, and caused most of simulated fuel oil system failures.

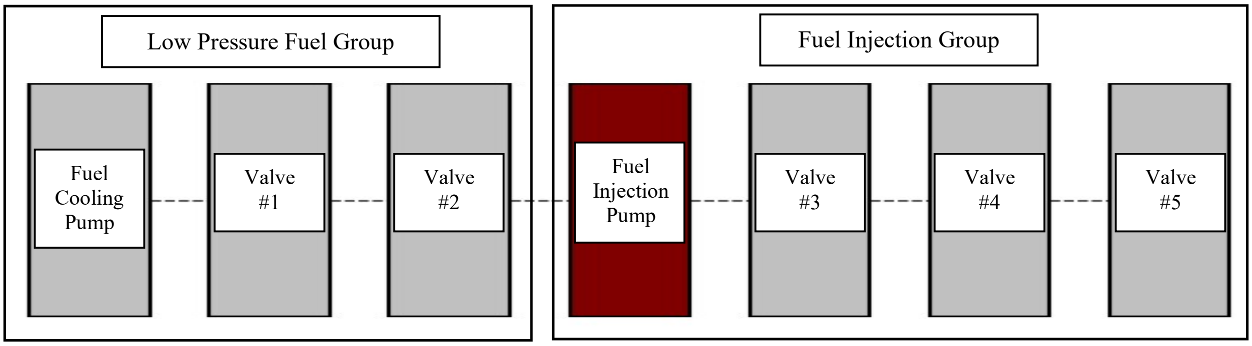

Figure 3: Initial Fuel Oil System Model

The reliability curve for the system was generated using the metrics for low pressure cooling pumps, high pressure fuel injection pumps and valves presented in the previous section. For this system the high-pressure cooling pump was the lowest reliability component in the system at each time step and was therefore equal to the system reliability over time. In testing, many configurations adding parallel redundancy of the cooling pump group for improving system reliability were tested.

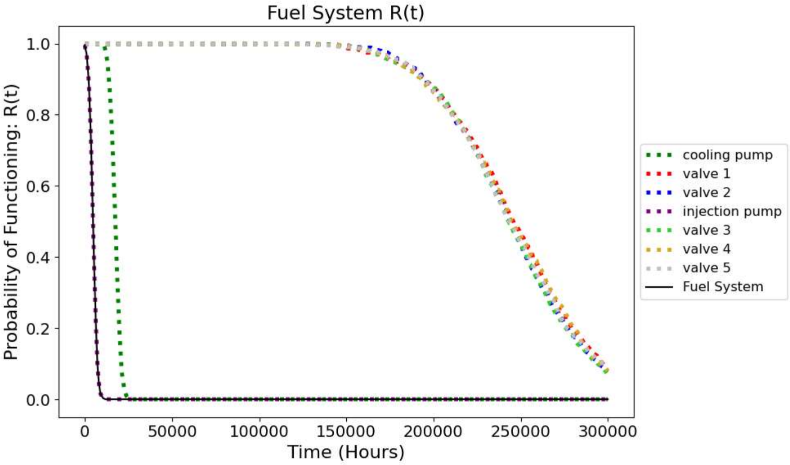

Figure 4: Initial Fuel Oil System R(t), Reliability over 100,000 operating Hours

System Weight Estimation

The components selected for the fuel oil and cooling systems were intended to support a 6-cylinder slow-speed diesel engine, MAN 6S70MC-C, with a maximum continuous rating of 16,780 kW operating at 91 RPM (MAN, 2009). This engine is a frequent choice for tankers and bulk carriers (Žan, 2009). The total weight of both two auxiliary systems combined was assumed to be 5% of the main engine weight. For the 550-ton engine this yields a total weight of 27.5 tons split between the total components in each system. To distribute this weight amongst the individual component's, catalogues were reviewed to determine a weight ratio between parts. The resultant total weight was then distributed amongst the individual components as seen in Table 2. The weight presented assuming inclusion of all necessary piping and fittings for each component, for example, high pressure fuel injection pumps may be double walled, so the casing and pipes and other subcomponents of the assembly were included in the estimated weight.

Table 2: Distribution of Total Auxiliary System Weight Between Components

Component	Quantity in Initial Systems	Individual Component Weight (tons)	Fraction of Total Initial Systems Weight (%)
Cooling Pump	2	5.64	41.07
Injection Pump	1	13.30	47.41
Heat Exchanger	1	2.70	9.82
Valves	8	0.05	1.70
Total Auxiliary Systems	12	27.50	100

From the calculated individual weights of components, the total weight of each proposed system was found. The total weight of the initial engine cooling system and fuel systems are presented in Tables 4 and 5 below.

Table 4: Distribution of Total Cooling System Weight

Component	Quantity in Cooling System	Individual Component Weight (tons)
Cooling Pump	1	5.64
Heat Exchanger	1	2.70
Valves	4	0.05
Cooling System	6	8.44

Table 5: Distribution of Total Fuel Oil System Weight

Component	Quantity in Fuel System	Individual Component Weight (tons)
Cooling Pump	1	5.64
Injection Pump	1	13.30
Valves	5	0.05
Fuel System	7	19.19

The next section explains parallel configurations required a component for switching between parallel lines. A cross-tie valve was placed between groups for this purpose. The fixed weight of this valve was 0.07 tons and was found using factors determined from marine valve manufacturer catalogues. This additional weight was factored into tested configurations having increased levels of redundancy. The reliability of the cross-tie valve is assumed to be the same as that utilized for all other valves.

TESTING PARALLEL CONFIGURATIONS

Redundancy in Testing

For testing the reliability of increased levels of redundancy, the groups were configured in different ways to determine the improvements to system reliability that could be gained from parallel component groups. For Tables 6 and 7, Test #0 outlines a system with no redundancy which was presented in section 2 of this report as the initial systems. For comparison, these systems are included as in tables and graphs in this section. Test #0 was the only configuration with no cross-tie valves. In the event of parallel groups, a cross tie valve is also added to the system between groups to allow for switching between lines. For all tested parallel configurations, the weight of the cross tie was also be added to the total system weight. An example configuration of the engine cooling system with parallel cooling groups, a singular heat exchange group, and a single cross tie is seen in Figure 5. This example is the same as Test #1, conducted for the fuel cooling system.

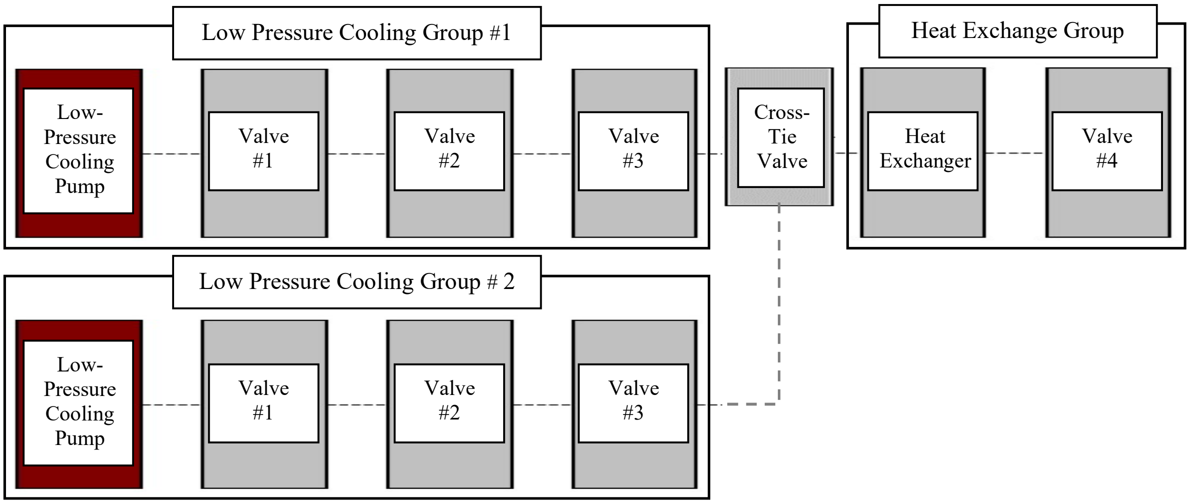

Figure 5: Test #1 of Engine Cooling System with Parallel Redundancy, 2 Cooling Groups, 1 Cross Tie Valve and 1 Heat Exchange Group

Cooling System Tests

For the engine cooling system, a total of 30 tests were conducted, with 12 presented in Table 6 below. Many of the test focus on increasing the number of cooling groups since the cooling pump is the most frequent cause of failure within the system. The tests presented within Table 6 highlight the general trends observed from simulations. Test #0-3 shows a single heat exchange group, Test #4-8 shows two heat exchange groups in parallel and Tests #9-12 shows 3 heat exchange groups in parallel. The number of parallel cooling groups is increased until the system failure is no longer completely determined by the cooling group. System weight was also limited to be less than 50 metric tons.

Table 6: Results from Cooling System Configurations Tested

Test #	# of Cooling Groups	# of Cross Ties	# of Heat Exchange Groups	Total Count of Components	System Weight (metric tons)	MTTF (Years)	Failure Rate (fails/MH)
0	1	0	1	6	8.54	3.02	11.94
1	1	1	2	11	14.40	6.04	10.14
2	1	1	3	15	20.19	9.05	7.95
3	1	1	4	19	25.98	11.81	6.64
4	2	1	3	17	22.94	8.95	7.07
5	2	1	4	21	28.73	12.07	5.99
6	2	1	5	25	34.52	15.09	5.20
7	2	1	6	29	40.31	17.91	4.86
8	2	1	7	33	46.10	21.03	4.68
9	3	1	4	23	31.48	11.97	5.43
10	3	1	5	27	37.27	14.89	4.73
11	3	1	6	31	43.06	18.01	4.41
12	3	1	7	35	48.85	21.03	4.11

As more cooling groups were added, the mean time between failure of each system increased, allowing for more operational time before the system would need maintenance services. The overall failure rate of the various configurations also decreased with the inclusion of multiple cooling groups. This which reflects higher reliability of the system caused by higher levels of redundancy, with mean time between failures increased by about 3 years per cooling group added in parallel. The tradeoff of this improved reliability is a much heavier system with a system weight increase of 60 % of the initial weight per cooling group in parallel.

For single heat exchange system configurations, Tests #0 – 4, the reliability of system was improved each time a cooling group was added to the parallel configuration. The reliability plot for Test #0, seen in the top left of Figure 6, shows the cooling group (blue curve) has a lower reliability at every time step then the heat exchanger group (red curve) and is the first group in the system to fail. In tests 1 to 4, the number of cooling groups in parallel increased by one each test. This additional redundancy moves the reliability curve the cooling groups to the right, indicating a longer time of high reliability and an extended mean time to failure of the grouping. Test 2 shows the system reliability is only partially determined by the 3 cooling groups in parallel, whilst in test #4 the system is no longer dependent on the failures of the cooling pumps at all, but instead on the heat exchanger group.

Investigating a system with two heat exchanger groups a similar trend persisted. The system reliability over time curve, R(t), was completely dependent on the cooling group reliability curve in Test #4, with only four cooling groups in parallel, whilst in Test #8, the addition of seven cooling groups in parallel pushed the reliability of the cooling group to be greater than that of two heat exchange groups.

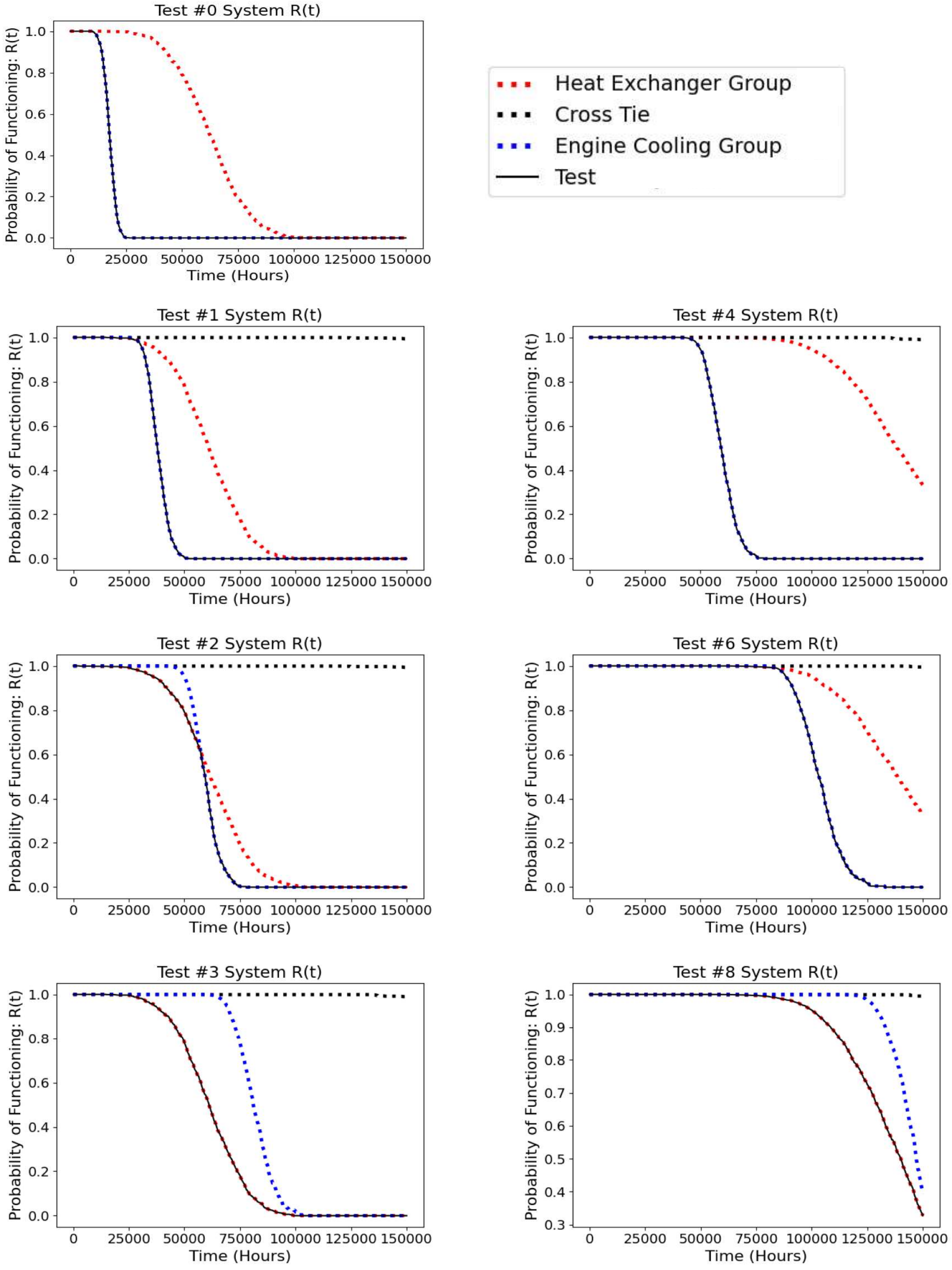

Figure 6: Engine Cooling System Single Heat Exchanger Tests #0, 1, 2, 3 (left), and Double Heat Exchanger Tests #4, 6, 8 (right)

Fuel System Tests

For the fuel system similar simulations were conducted. Fuel injection groups were added in parallel until the system reliability was no longer entirely dependent on failure of the fuel injection group. Test #0-7 considered single cooling group with varied numbers of redundant injection groups. Test #8-10 investigated system configurations with 2 cooling groups, and tests #11 was the only simulated test configuration including triple cooling groups. The fuel injection pump was the heaviest part considered in this report, so the system weight was found to be increasing even more rapidly than the previously tested cooling system, when adding more fuel injection groups. A total of 30 systems were investigated in simulation but only the systems weighing less than 100 metric tons in total are presented in Table 7.

Table 7: Results from Fuel System Configurations Tested

Test #	# of Cooling Groups	# of Cross Ties	# of Injection Groups	Total Count of Components	System Weight (tons)	MTTF (Years)	Failure Rate (fails/MH)
0	1	0	1	7.00	19.19	0.79	30.29
1	1	1	1	8.00	19.26	0.77	22.19
2	1	1	2	12.00	32.71	1.53	27.32
3	1	1	3	16.00	46.16	2.34	18.66
4	1	1	4	20.00	59.61	3.12	14.83
5	1	1	5	24.00	73.06	3.86	12.54
6	1	1	6	28.00	86.51	4.64	10.92
7	1	1	7	32.00	99.96	5.46	9.55
8	2	1	4	23.00	65.35	3.11	14.47
9	2	1	5	27.00	78.80	3.94	11.78
10	2	1	6	31.00	92.25	4.70	10.57
11	3	1	6	34.00	97.99	4.65	10.01

As of the fuel injection groups, the group with the lowest reliability components, were added in parallel the mean time between failure of the system increased while failure rate reduced. This is desirable as the system will be more likely function over extended periods of time. The weight increase cost for this increased system reliability was approximately 70 % the original system weight per injection group added in parallel. This weight cost in many cases might not be justified by the minimal increases in mean time between failures and reductions in failure rate for some applications, so an optimum configuration would be based on a desired the operational time. Applicability of these results is discussed more in the next section.

Observing the reliability over time plots of the tests presented these trends can be better understood visually. The low variance of the fuel injection failures results in an almost vertical reliability curve, this corresponds to components whose failures occurred at approximately the same time every time it fails. The high variance of failures of the cooling groups leads to a much more spread reliability curve. Presented in Figure 7, the right side shows reliability curves for a singular cooling group and two, four and seven parallel injection groups considered in Test #0, #1, #4 and #7. The right side of Figure 7 shows reliability over time for Tests #8, #9, and #10, which considered two cooling groups and four, five, and six parallel injection groups.

For both sets of tests, the addition of parallel injection groups shifts the reliability curve for these groups minimally and corresponded to a small increase in mean time between system failures. Looking specifically at the right column of figure 7 we see per injection groups added, the reliability curve moved right about 12,000 hrs., this corresponded to an increase mean time to failure of less than 1.5 years. The weight of three injection groups however is more than 30 tons. Addition of such a heavy group, for a low tradeoff in increased reliability over time is not justifiable in for any design where being lightweight is desired. This is more important for vessel which operate at high speeds or in shallow waters and seems to be less relevant for heavy vessels such as bulk carriers and tankers.

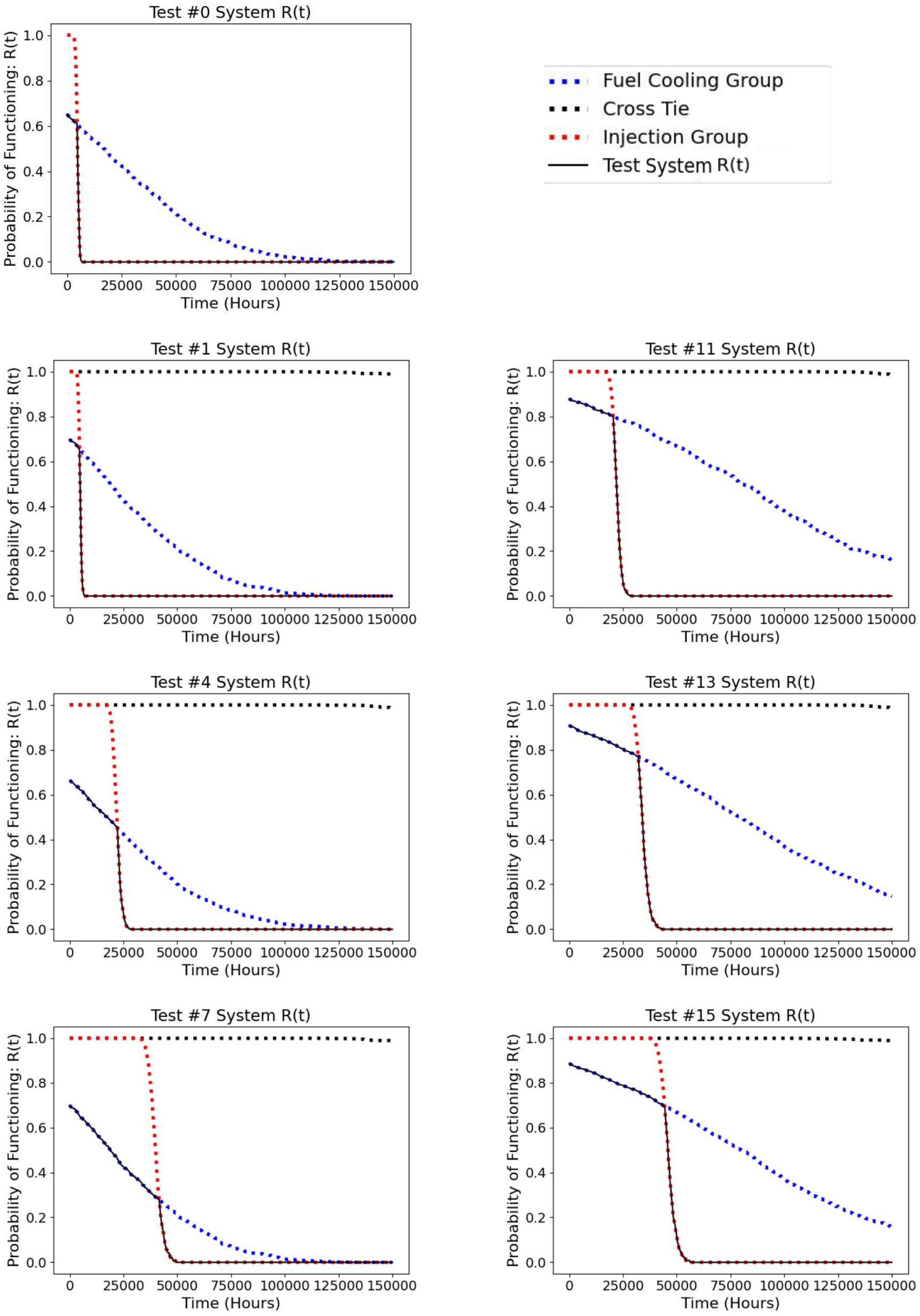

Figure 7: Fuel System with Single Cooling Group, Tests #0, 1, 4, and 7 (left), and Double Cooling Groups Tests #11, 13, 15 (right),

APPLICATION OF TEST RESULTS

From the resulting reliability metrics of various system architectures tested, a level of redundancy needed for desired performance can be quickly decided for a specified mission lengths. The few crewless vessels existing today have a maximum operational range is 2000Nm at 16 Knots (Ziajka-Poznańska & Montewka, 2021). This application of autonomous vessels corresponds to only 125 hours of autonomous operations. A long-term goal could be to have the vessel operate autonomously for months to years at a time with no on-board human interference. This goal will only be achieved if a highly reliable machinery system is implemented. Using the results from the test cases, an optimal configuration for the cooling and fuel oil systems can be selected for an autonomous vessel operating for 1, 2 ,3, 4, and 5 years at a time. The optimal system was selected with emphasis on reliability of at least 30% probability of functioning until the end of each desired mission length, as well as minimizing the weight of the system.

Table 8: Cooling System Performance of Optional Configurations over Various Mission Lengths

Mission Length (years)	# of Cooling Groups	# of Cross Ties	# of Heat Exchange Groups	Total Count of Components	System Weight (tons)	System Reliability at the end of the Mission Length
1	1	0	1	6	8.54	99.9 %
2	1	0	1	6	8.54	53.8 %
3	1	1	3	15	20.19	99.5 %
4	1	1	3	15	20.19	96.5 %
5	1	1	3	15	20.19	88.6 %

The cooling system, at the beginning of its operation would highly reliable because of its higher reliability components compared to the fuel oil system. As seen in the curves present previously, most components in this system do not fail until about 25,000 Hrs. which is after approximately 3 years. This being known, the initial configuration is optimal for mission lengths on 1 or 2 years but for 3-5 years of operation, a more redundant configuration would be the more optimal choice for reliable system performance. The fuel system on the other hand was shown to fail much earlier than the cooling system in its initial configuration and this leads to a much more diverse selection of optimal architecture dependent on increasing mission lengths as seen below.

Table 9: Fuel System Performance of Optional Configurations over Various Mission Lengths

Mission Length (years)	# of Cooling Groups	# of Cross Ties	# of Heat Exchange Groups	Total Count of Components	System Weight (tons)	System Reliability at the end of the Mission Length
1	1	1	2	12	32.71	62.9 %
2	1	1	4	20	59.61	49.3 %
3	1	1	5	24	73.06	40.8 %
4	1	1	6	28	86.51	34.8 %
5	2	1	8	39	119.15	70.5 %

The goals presented here are assuming complete autonomy of the vessel and continuous operation, but in practice would require a consideration of scheduled inspections for maintaining the vessel, as well as stops to prevent overloading or over heating of equipment. These considerations are not made in this paper but would be needed for a real-life implementation.

CONCLUSIONS

This paper has presented the tradeoffs between increased reliability through parallel configurations at the expense of increase system total weight. Investigations showed that low reliability components should be the focus of parallel options if reductions in system failure rate and increases to mean time between failures are desired. Simulated results for multiple configurations of cooling and fuel oil system have been presented. Pumps proved to be the most common failing components investigated in both systems, cooling water pumps in the cooling system and fuel injection pumps in the fuel oil system.

Testing of parallel configurations revealed a considerable increase in system weight for improvements in system reliability. The necessity of these improvements in reliability should be determined by the application specific needs, whether that be a desire to remain highly reliable or lightweight. These results were tested and normalized over various mission lengths to find optimal configurations for 1, 2, 4, and 10 years of system operation. The results from this investigation reaffirm that the selected level of redundancy should be based on specific mission criteria required rather than classification society rules to result in highly reliable autonomous operations. Future studies may investigate lighter weight or higher reliability components for increases to system reliability over time for a lower increase in system weight. Additional parameters such as cost of components should be considered in future work if they are available.

The majority of this work was completed using estimated values but for companies and organizations that have similar data available to them, this statistical analysis approach could be utilized. Methods for estimating reliability metrics and system weights presented here are repeatable and using this information, various configurations could be simulated and compared. Following such simulations, a predetermined mission length can be used to decide and the most reliable configuration for this requirement.

CONTRIBUTION STATEMENT

Andreya Ware: Conceptualization; Software; Investigation; Writing – original draft.
Matthew Collette: Conceptualization; Supervision; Writing – review and editing.

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