Reliability study of Alternative Fuels used for a ferry's plant efficiency

Iraklis Lazakis (M)**, Thomas Kourakos** (SM)

Batteries could be the near-term solution to the increasing Green House Gas Emissions problem and could also be a part of the future of the marine industry. If their role as storages of energy was combined with the production of "green" electricity, batteries would be an alternative to the traditional fuels with zero environmental footprint and thus a "green" solution. This study is investigating the reliability of a ferry diesel-electric propulsion system, after a multi-annual operation. The Dynamic Fault Tree Analysis method is used to analyse the propulsion system and detect any system failures and the components that cause them. After the analysis is complete a maintenance table is created for the least reliable components of the systems describing the approximate operation hours that when reached the component should be inspected and get replaced or repaired.

INTRODUCTION

The global merchant fleet in 2021 is estimated to have reached 53,973 vessels according to the European Union (ROBERTS, 2021). However, this achievement came at the cost of environmental pollution, which augments each year. In 2014 IMO introduced the energy efficiency design index regulations, as a measure to control the increase of CO2 emissions produced by the shipping industry (IMO, 2014). IMO published that shipping is accounted for about the 2.2% of the total global carbon emissions and if this path is to be followed, emissions by 2050 could represent 90%-130% of these of 2008 (IMO, 2008) (IMO, 2014).

Considering the decarbonisation era marine industry has entered, new zero-emission "eco-friendly" fuels are considered, such as hydrogen, ammonia and methanol in order to replace the fuels that are currently used. Another powering system for a vessel that was also introduced in the effort of decarbonizing marine industry and became rapidly operational are battery systems. A variety of ships are designed to operate only with batteries or in a combination of batteries and diesel (consisting a hybrid power system).

The main aim of this project is to research the reliability of the engine system of a hybrid ferry following a certain methodology and use its results to make suggestions regarding the inspection of the system and its components.

LITERATURE REVIEW

Batteries and Hybrid systems

Battery is a device that stores chemical energy and converts it to electrical energy. Ships use re-chargeable batteries which can be charged again after they are discharged by applying DC current to its terminals. This application is the reason batteries form a non- carbon solution, as no fossil fuels are used in their operation. Thus, they form an important factor that could eventually lead to the complete decarbonisation of the shipping industry. Batteries re-charge from shore power facilities and at present approximately 2000 ports exist around the globe, with the proper infrastructure. And all of them could have the potential to be charging stations for the docking ships. This case would be viable in the long term under the conditions that ships in the future could be powered by a battery-only system (completely electric-powered ships), which in combination with the produce of 'green-electricity' to re-charge the batteries, would lead to a zero-emission marine industry.

Currently a hybrid powering system is operating in a variety of ship types, such as offshore supply ships, tugs, Ro- Ro cargo ships and other offshore vessels, but is not yet applied to the ocean-going vessels. A hybrid power system is the combined operation of a diesel-electric power plant with a battery system, which has a supplementary role. An expanded application of a hybrid system could be a transitional solution to the way of decarbonisation as it could result to an 'economy' of carbon-emissions (Klebanoff, 2021).

The applications battery systems could have on ships are still under research by investigating the various possible electric propulsion designs. Lan et al. have made a research regarding the optimum size of a ship, whose powering system is consisted of solar energy, batteries and diesel generators. The aim of this study was to reduce as much as possible the cost of constructing and operating of the vessel as well as the CO_2 emissions produced. Misyris et al. created an algorithm with its use being the illustration of the state of the battery system for the operation duration of the ship.

Analysis Tools

In order to assess the reliability of the battery system installed on a ferry Failure Modes and Effect Analysis (FMEA), Dynamic Fault Tree Analysis (DFTA) and Event Tree Analysis (ETA) tools are considered to be used. FMEA and DFTA are reliability analysis tools and each one represents one of the two major categories analysis tools are divided:

- Qualitative (FMEA)
- Quantitative (DFTA)

FMEA is used in order to review the desired system by providing detailed information to find and address the failures and their causes. A bottom-up approach is used that goes through the overall malfunction of the system. There are three aims to be achieved by using this tool; to classify potential failure events and their effect on the various components of the system according to their degree of importance, propose actions to prevent the failure events, to discover methods that may lessen the effects of the failure events.

This is a peer-reviewed, version of record of the following paper: Lazakis, I., & Kourakos, T. (2023). Reliability study of alternative fuels used for a ferry's plant efficiency. 1-7. Paper presented at SNAME student section, Glasgow, United Kingdom.

As every tool FMEA has advantages and disadvantages, with them being:

Advantages:

- It is user-friendly as changes and adjustments can easily be done on the product design,
- Introduction criteria for the investigations,
- Determination and identification of the failure moments,
- Development of an efficient research methodology.

Disadvantages:

- Needs to be updated constantly as new failure modes may be discovered,
- Failure in identifying or taking not account a mode, may lead to depreciation of the risk,
- The user needs an expert knowledge of this software (Ribas, 2021)

FTA is a commonly used analysis tool in research case studies for the last 60 years (since its introduction). It utilizes a deductive method (top-bottom) of analysis, with its aim being to define the causes or combination of causes that lead to the top event (Lazakis, 2018). This tool has a well-organised and highly detailed format, which is constituted of:

- A top-event (top-gate),
- Intermediate events (gates) and
- Basic events

This format shows the linked chain and the process in which the basic events result in the failure of the top gate.

Also it leads to the finding of all the autonomous components that have an influence on the happening of the top gate and consequently the reliability of the top events of the system. If FTA is also provided with numerical data, it can be a both qualitative and quantitative analysis tool. This kind of analysis needs an expert knowledge of the system under investigation, and this is a reason its results are highly valued (Lazakis, 2018).

The advantages of FTA are 'moving around' the useful analysis it provides, as very complex systems can be analysed due to its deductive set-up and the reliability, frequency the failure occurs, and unavailability of the system can be calculated very easily. The analysis tool's disadvantages are mostly focused on the difficulty of the tool to analyse very complex systems as if not properly organised the illustration of the system may be chaotic and if a system is too complex the simulation part may 'crash' several times. Also in FTA the gates and events should have unique names as similarity may lead o a confusion at the calculation part (Ribas, 2021).

ETA is similar to FTA proses as it uses a deductive method to analyse the system and is used for determining and identifying the risks that refer to a technical system. This tool also analyses the various negative operational fluctuations or failures of a system after the occurring of an event. Similarly to FTA it is based on Boolean algebra and is applied mainly before a system becomes operational, anticipating this way any malfunctions or failures that may occur after it becomes operational. ETA can be used in creating a preliminary risk assessment, to avoid any errors from happening (Ribas, 2021).

METHODOLOGY

In this chapter the methodology implemented in this research is expanded in steps and the flowchart showing the interconnections of these steps is illustrated in Figure 1.

1) Collecting the initial information and data for MV Catriona's engine system. The components that the engine system is consisted of and their failure rates during the wanted time period were needed.
2) Organising the propulsion system in "levels" and 'sub-levels" that are interconnected.
3) Formation of the Fault Tree based on the above-mentioned division of the propulsion system.
4) Performing the required iterations on the FT in order for the results delivered to respond to real life operation process.
5) Presentation of the results.
6) Discussion on the reliability of each system, sub-system.
7) Provide useful suggestions for the inspection of the system.

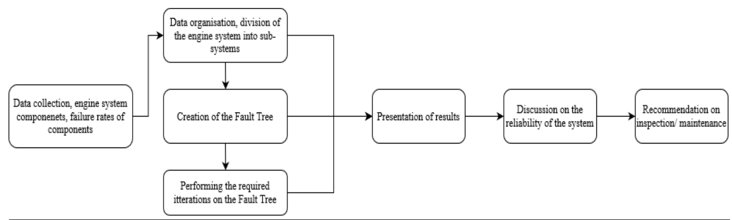

Figure 1: Flowchart of methodology

CASE STUDY

The details of this case study regarding the ship type and propulsion system, the gathering and organisation of the data, the calculations, the set-up of the Fault Tree, the iterations and the service plan of the engine system are included in this chapter.

Introduction to MV Catriona's engine system

In 2015 CalMac launched an innovative hybrid ferry MV Catriona, to which the machinery that the propulsion system consists of is:

- 2 Electric Motors
- 3 Diesel Generators
- 2 Battery Banks

The engine system of MV Catriona is divided in 4 sub-systems: D/G 1, D/G 2, D/G 3, and Battery Bank.

Each D/G is divided in 5 systems with them being Cylinder System, Pump System, Valves and Filters System, Alternator System and the rest of mechanical parts that could not be introduced to the other systems, but their operation was significant to the overall engine system.

After gathering all the main components that construct the engine system and dividing this system in the sub-systems mentioned above, the failure rates of the components needed to be found and calculated.

The OREDA Offshore Reliability- Data Handbook 4th Edition was used for the obtaining of the failure rates (Oreda, 2002), as

in this handbook, there are diesel generators used that are of a similar type as the ones installed in MV Catriona.
In OREDA the failure rate of the diesel generator as a system is provided as well as the percentage of malfunction occurrence of each component to the system failure. Thus the following equation was extracted in order to calculate the failure rate of each component:

$$Failure\ rate\ of\ the\ part = \frac{Percentage\ of\ occurence * Total\ failure\ rate\ of\ D/G}{100} \quad (1)$$

Development of Dynamic Fault Tree

The creation of the Fault Tree was done according to the earlier mentioned division of the engine system to sub-systems. In the following figures the arrangement of each system to each initial components is presented.
Electric motor system as mentioned above is composed by the 3 diesel generator systems and the two battery systems that illustrates as one, but numerically is taken into account as two.

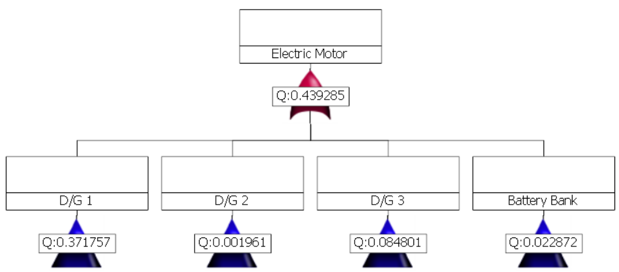

Figure 2: Electric Motor system FT

The D/G 1 arrangement is shown below, but as all the diesel generator systems in this research are arranged in the same manner it is considered to be universal. The same logic applies and for all the diesel generators' sub-systems.

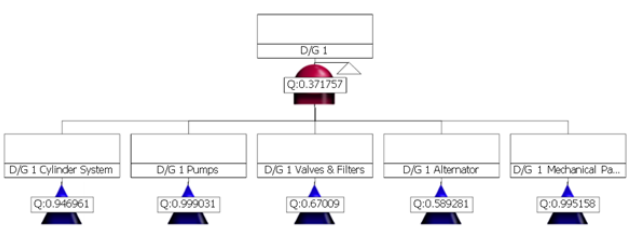

Figure 3: Diesel Generator system FT

The cylinder system is divided in two major parts, the piston system and the cylinder head system. These two systems are then composed by their components, which are chosen in the same philosophy as they appear in OREDA Handbook "components form the lowest level (meaning of the Fault Tree) items that are being repaired or replaced as a whole" (Oreda, 2002).

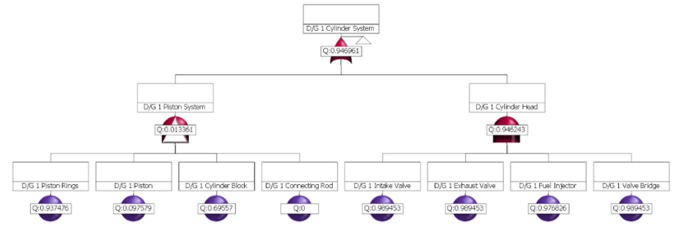

Figure 4: Cylinder system FT

The remaining sub-systems are presented below. The Valves and Filters system consisted of the main valves and filters that with their failure or malfunction in operation they influence the operation of the diesel generator. The pump system composed of the main pumps used in the diesel generator (i.e. fuel, cooling water, lubricating oil pumps). The alternator system that converts the mechanical energy produces to electrical one. The mechanical parts system in which as mentioned above is the system where the components that could not be added to the rest systems, added to this one as any failure or malfunction they could have affected immediately the operation of the diesel generator. And finally the battery system (Battery Bank system), which is divided in the composing parts of a lithium battery.

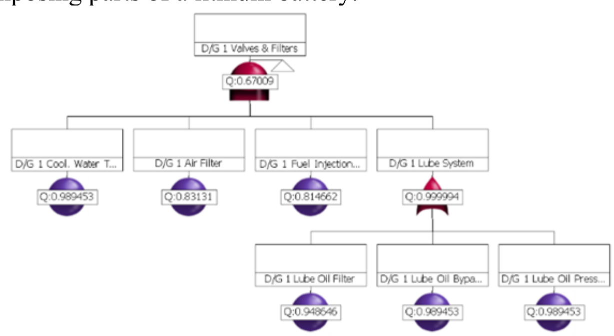

Figure 5: Valves & Filters system FT

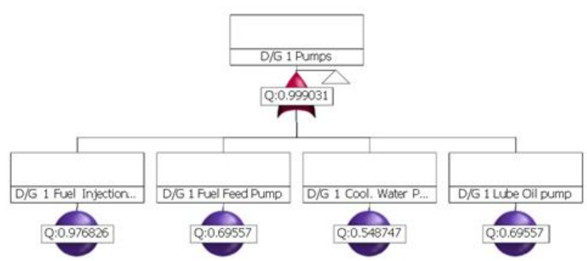

Figure 6: Pumps system FT

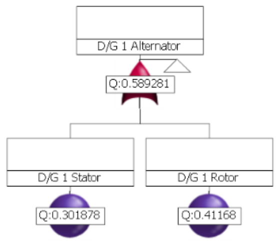

Figure 7: Alternator system FT

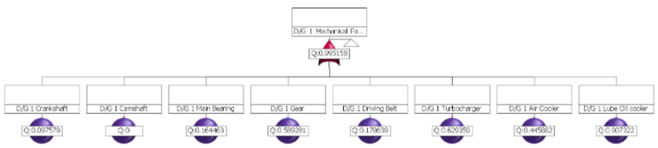

Figure 8: Other mechanical parts FT

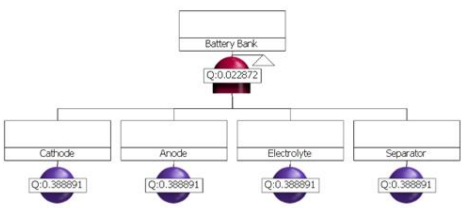

Figure 9: Battery bank system FT

Calculations and Iterations of the Dynamic Fault Tree

Before the simulation started the percentage of exposure of its diesel generator had to be added. This is the average percentage that each diesel generator is used for the wanted time duration. These percentages were set as follows, 40% for D/G1, 30% for D/G2, 30% for D/G3.
The time period that the vessel is under investigation is a 5 year operational period (i.e. 60 months) and the steps set are 3 month time steps.
After the first simulation run there had to be made various iterations in the fault tree gates regarding the types used, the arrangement of some gates and events, and finally an overall re-arrangement of the diesel generators' sub systems.
These changes took place for two main reasons regarding the results delivered by the simulation. The results were numerically inaccurate as the values were not representing the real life operation and the cut sets (chains) which appeared to be causing the system failure were not realistic and could not happen in normal operation process.
Also another change in the fault tree was the consideration of the two battery banks as one, due to the crashing of the software during the simulation. All the needed changes in the data input were made for this combination not to affect the numerical results.

RESULTS

The results of the iterations and commentation on them are presented in this chapter.
When all the needed iterations were done the final simulation took place and the results for each system were extracted.
As the PTC Windchill software calculations show the unreliability of the system, these numbers need to be subtracted from 1, in order to get the reliability percentage. An equation made to graphically represent the subtraction is shown below:

$$Reliability\ value = 1 - Unreliability\ value \qquad (2)$$

Electric Motor Results

The results of the simulation of the electric motor system for a five year period are presented in the plot below.

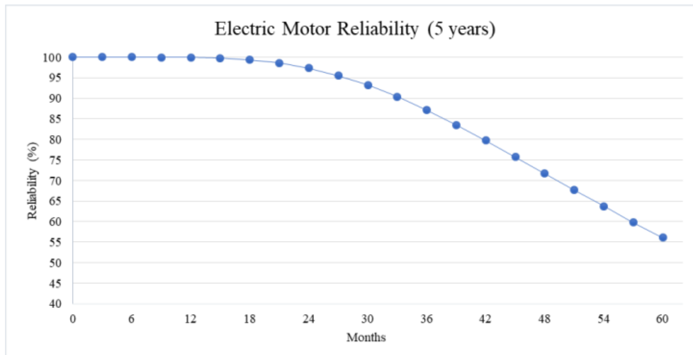

Figure 10: Reliability of Electric Motor system

The reliability of the electric motor for the first 33 months decreases only 10%. Taking into account that this engine arrangement still is a relatively new technology and also considering the planned maintenance in this time period, the results are overall satisfactory.

Electric Motor sub-systems

Taking into account the percentages according to which the diesel generators operate the difference in the reliability decrease shown below is justified.

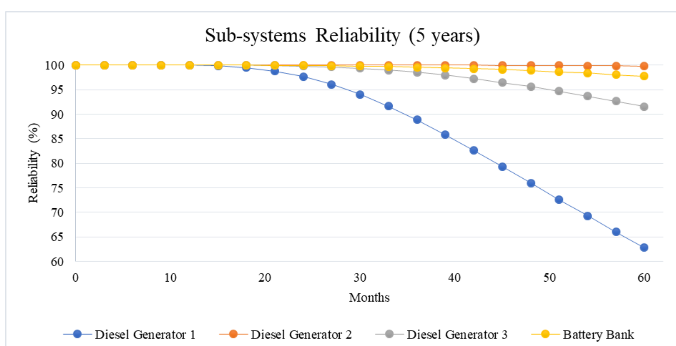

Figure 11: Reliability of Electric Motor sub-systems

Diesel generators 2 and 3 have a difference in their reliability decrease percentage that is around 9% and is most certainly caused by the place they have in the Fault Tree.

The battery banks, which are the system that is mostly under investigation see a decrease of only 2.3%, and thus are considered as a highly reliable system for a 60 month operational period.

Least reliable D/G sub-systems

The least reliable sub-systems of the diesel generator systems are the cylinder systems ad pumps systems. Below are presented the decrease of their reliability and the comparison of each one with its corresponding to the other diesel generators.

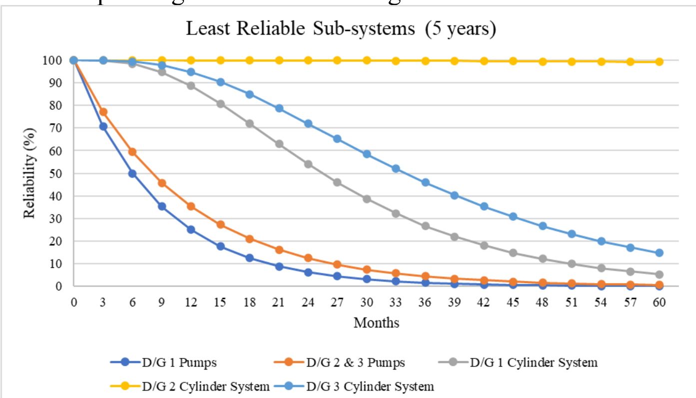

Figure 12: Least Reliable sub-systems of the D/Gs system

The most unreliable systems appear to be the pumps systems as their reliability decreases to 25%-35% in one year, in 27 months it falls below 10% and in 54 months practically becomes zero.
The second least reliable sub-system is the cylinder system, but this appears to fluctuate between the diesel generators. A large decrease happens for D/Gs 1 and 3, but for D/G 2 the reliability decreases only 1%. For D/G 1 and 3 the reliability reaches 14.8% and 5.3% respectively. This difference in numbers of D/G 2 could be due to the positioning in the Dynamic Fault Tree, as it has been observed in other cases. This has been a challenge posed throughout the development of the Fault Tree, but handled to most of the cases. However in this particular case the results of D/Gs 1, 3 are considered the logically and practically correct ones and the inspection plan for the referred components was created based on them.
The rate of reduction is not very high in this case as 15 months are needed for D/G 1 to reach 80% and 21 months for D/G 3.

Alternator & Valves and filters systems

The two remaining systems are the alternator and the valves and filters systems. Their reliability remains relatively high, but varies for each diesel generator.
The alternator's reliability in a 60 month period does not fall below 40% for diesel generator 1 and 50%, 80% for diesel generators 2 and 3 respectively.

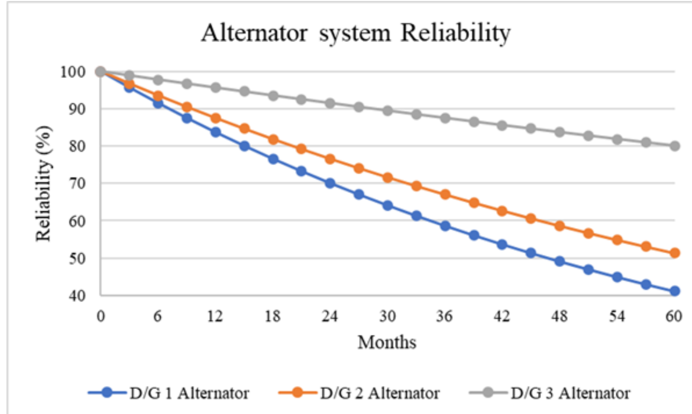

Figure 13: Reliability of Alternator system

The reliability of diesel generator 1Valves and filters system reaches 32% in 60 months, but needs 30 months to reach 70%. The reliability values for diesel generators 2, 3 are the same thus they shear the same line in the diagram. Their reliability remains high for a long period; reaches 80% in 33 months.

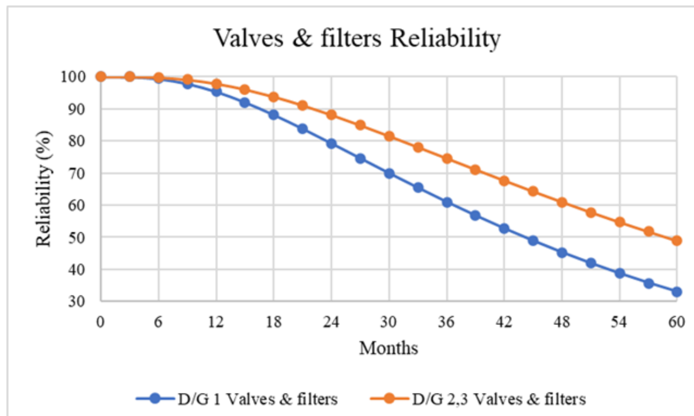

Figure 14: Reliability of Valves & filters system

Inspection Plan

The maintenance plan created and proposed for the MV Catriona's engine system and mainly for the diesel generators' least reliable components is based on logical observation of the reliability reduction of each sub-system (caused by the failure rate of the components). In the following table the analytical maintenance plan is presented. On the left side of the table are the diesel generator and its sub-system where each component belongs and on the right side the suggested time (operational hours) that when reached the repair or replacement (depends on the component) of the component should be done.

Table 1: Suggested time of repair/replacement of least reliable components

Diesel Generator	Sub-System	Component	Suggested Service/ Replacement (hours)

D/G 1	Cylinder System	Piston Pings	10800
		Intake Valve	8640
		Exhaust Valve	8640
		Fuel Injector	8640
	Valves & Filters system	Lube Oil Filter	1440
		Lube Oil Pressure Regulating Valve	1440
		Lube Oil Bypass Valve	1440
	Pumps System	Fuel Injection Pump	2160
D/G 2	Cylinder System	Piston Pings	8640
		Intake Valve	8640
		Exhaust Valve	8640
	Valves & Filters system	Lube Oil Filter	1440
		Lube Oil Pressure Regulating Valve	1440
		Lube Oil Bypass Valve	1440
	Pumps System	Fuel Injection Pump	2160
D/G 3	Cylinder System	Piston Pings	15120
		Intake Valve	12960
		Exhaust Valve	12960
		Fuel Injector	12960
	Valves & Filters system	Lube Oil Filter	1440
		Lube Oil Pressure Regulating Valve	1440
		Lube Oil Bypass Valve	1440
	Pumps System	Fuel Injection Pump	2160

The components presented in Table 1 are as mentioned above the least reliable components of the Fault Tree resulting in certain failures. When the piston rings wear out, they lead to a not proper operation of the piston system and thus to a not proper operation of the cylinder system. In the same manner the failure or malfunction of the intake and exhaust valve and the fuel injector (in D/Gs 1 and 3) have as a result the failure of the cylinder head system and thus the failure of the cylinder system. The lube oil filter, lube oil pressure regulating valve and lube oil bypass valve lead to the failure of the lubrication system and of the valves and filters system. And finally any malfunctions or failures to the fuel injection pump have as a result the not proper operation of the pumps system.

The proposed repair time of each item on this table is based on when during the analysis the item's reliability started to decrease significantly, and thus the life span of the item reached its end. The time suggested is not the exact as the point in which the reliability started reducing, but a certain time margin was considered. This time margin was taken into account as hurdles may occur, such as the exact decrease point of the reliability (end of life span of the item) is reached when the diesel generator is operating and so the repair or replacement is not possible to happen right away, or the spare part needed for the replacement of the worn out item does not reach the ship in time or is not directly available, or other more serious issues occur and the proper operation of the diesel generator is needed. These and many other practical reasons may lead to a delay of the repair of an item and so a small period of time is taken into account.

The inspection plan created was further compared and validated with CalMac's own inspection plan; either provided by the manufacturer or followed by the empirical knowledge and on practice observation of the engineers on board.

RESULTS ANALYSIS

The engine system of MV Catriona by having installed an electric motor in the place of a diesel engine combines the partial decarbonisation of the ship and concurrently the increase of reliability of the engine system, as the electric motor requires less maintenance (Wang, 2021).

In this thesis the reliability this engine system was investigated and its components that may lead to a system failure were identified. With the use of PTC Windchill software the system was analysed for the operational period of 5 years, and with the use of Dynamic Fault Tree Analysis tool the reliability of the system and its sub-systems was studied.

Taking into consideration that a ferry is not fully operational for 5 years continuously, as scheduled maintenance processes or extreme weather phenomena etc. may occur, the results of the research are overall satisfying. The reliability of the engine system remains over 85% for 39 month fully operational period. The reliability of diesel generators 2 and 3 reduces to 99% and 91% respectively after 60 months have passed and diesel generator's 1 falls to 62%, but this is understandable as diesel generator 1 has the biggest usage percentage of the three, 40%.

The reliability of the parts that were the reason of this research, the battery banks remain very high throughout the five years, reducing only by 2.3%.

The sub-systems of the diesel generators have various fluctuations, but considering the different components they consist of and their different operation the fluctuations are justified. The least reliable components that lead to the failure of the of the system that they fall under, and by extension to the reduction of the reliability of the diesel generator system, have been identified and included in a maintenance table. In this table the time for repair or replacement of the components is suggested, which is described by operational hours. The results obtained by this researched have been validated by the existing literature, the OEMs provided and used and the supervisor.

CONCLUSION

The analysis of this engine system was based on data provided by CalMac and obtained by OREDA Handbook (Oreda, 2002). If more time was available for the research and gathering of data surely more accurate results would be provided regarding the reliability of the system, as more time for observation and monitoring of the engine system and sub-systems and their failures, and more analysis tools could be used enrich the research with further information.

In the future the FMEA tool could be used providing significantly useful results on this research on the failures and their causes and also propose measures to either prevent or lessen the effects of the failures. The use of FMEA could also be of great help for the accuracy of the maintenance table. But for this to be possible more time and detailed data need to exist. Further to the future work, monitoring of the failures of each component, with the use of electronic means, might be achieved and in combination with a human analysing the means of operation the ferry's engine was under, could produce a very detailed plan of service and maintenance. This plan combined with the inspection and service manuals provided by the manufacturer would be a highly valuable tool for the engine team supervising the vessel and could also lead to avoidance of several malfunctions or system failures.

AKNOWLEDGMENT

The greatest help was provided by Dr. Lazakis throughout every step of this project. His contribution to this project has been invaluable. His very effective collaboration, his expertise, willingness to help and very useful and important suggestions made this project possible and a place not only of learning, but also of deep understanding.
Great appreciation I would also like to express to the CalMac engineers for their trust in me with confidential information and data in order to enrich this project, as well as their further help and collaboration on validating the results of the project.

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